

Monday, July 27, 1998
ACHONDRITES
9:00 a.m. Walton Theatre

Chairs: T. J. McCoy
M. Wadhwa

McCoy T. J.* Dickinson T. L. Lofgren G. E.

Partial Melting of the Indarch (EH4) Meteorite: A Textural View of Melting and Melt Migration

Fogel R. A.*

High-Sulfur/Low-Iron Silicate Melts: Low-Oxygen-Fugacity Phenomena of Importance to Aubrite Formation

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Petrology and Geochemistry of Lodranite Graves Nunataks 95209

Klöck W.* Nakamura K. Maetz M. Arndt P.

Zinc Contents of Ureilite Silicates

MacPherson G. J.* Ash R. D. Rumble D. III

In Situ Laser Microanalysis of Oxygen Isotopes in Ureilites

Franchi I. A.* Sexton A. S. Pillinger C. T.

Oxygen-Isotopic Variation in the Bencubbin Meteorite: An Exotic Component in the Matrix?

Wadhwa M.* Zipfel J. Davis A. M.

Constraints on the Formation History of Brachinites from Rare-Earth-Element Distributions

Goodrich C. A.*

Brachinites: Residues from Low Degrees of Melting of a Heterogeneous Parent Body

Arai T.* Takeda H. Papike J. J. Shearer C. K. Miyamoto M.

Rare-Earth-Element Abundance of Pyroxene and Plagioclase in a Pristine Euclitic Basalt, Yamato 75011,84

Kaneda K.* Warren P. H.

Iron-Nickel Metal Bearing Unique Euclitic Elephant Moraine 92023: Its Petrography, Siderophile Concentrations, and Petrogenesis

Warren P. H.*

Howardite-Euclitic-Diogenite Magma Ocean Petrogenesis: Equilibrium or Fractional Crystallization?

PARTIAL MELTING OF THE INDARCH (EH4) METEORITE: A TEXTURAL VIEW OF MELTING AND MELT MIGRATION. T. J. McCoy¹, T. L. Dickinson², and G. E. Lofgren^{3,1} Department of Mineral Sciences, MRC 119, Smithsonian Institution, Washington DC 20560, USA (mccoy.tim@nmnh.si.edu), ²National Science Foundation, 4201 Wilson Boulevard, Arlington VA 22230, USA, ³Code SN2, NASA Johnson Space Center, Houston TX 77058, USA.

Introduction: Aubrites are breccias composed of FeO-free, mafic silicates, plagioclase, Si-bearing metal, and unusual sulfides (e.g., oldhamite, alabandite). Textural features [1–4] suggest a prolonged thermal history with high degrees of partial melting, melt migration, crystallization and slow cooling. Experimental studies [5,6] have not focused on textural and melt migration features. We have conducted experiments on the Indarch (EH4) enstatite chondrite and emphasizing textural aspects of melting and melt migration, and implications for melt crystallization [7].

Experimental Technique: A detailed description of the experimental technique is given in [6]. Each experiment utilized ~160 mg of powdered Indarch, producing charges ~5 mm in diameter. Solid metal buffers (Cr,V) were used in combination with graphite crucibles to maintain the appropriately low oxygen fugacity. Charges were sealed in evacuated silica tubes and run at 1000°–1500°C for 4–24 hrs. Phase identification was confirmed with the electron microprobe. Modal analyses of 400–650 points/charge were conducted.

Results and Discussions: We discuss silicate melting and sintering, metal-sulfide melt segregation, and implications for the crystallization of these melts.

Silicate Melting and Sintering. Indarch silicates include enstatite, plagioclase, free SiO₂ and FeO-bearing pyroxene [6,8]. Silicate melting begins at 1100°C and plagioclase, SiO₂ and FeO-rich pyroxene are exhausted by 1200°C (~9% silicate melting). The degree of silicate partial melting increases with temperature, and forsterite crystallization is observed at 1400°–1450°C. At 1500°C, silicates are completely melted.

The 1000°C charge contains ~50% void space. The 1200°C exhibits ~10 vol% silicate partial melting and only ~35 vol% void space, producing a coherent charge. By 1400°C, silicate partial melting has reached ~20%, the charge is spherical with no appreciable void space, and enstatite grains have coarsened from ~100 µm to ~300 µm. Limited melt migration is observed at 1425°C. At 1500°C, the charge is completely melted.

Metal Melting and Segregation. All of the metal and sulfide phases melt by 1000°C, suggesting they all participate in melting at the Fe,Ni-FeS cotectic (988°C). At 1000°C, each of non-silicate melt

components occur as distinct, small (~10 µm), irregular grains throughout the charge. At 1200°–1425°C, the metal is intergrown FeNiSi and C-bearing metal. At 1400°–1425°C (~25% silicate melting), large compound (≤3 mm) metal-sulfide spheres are present. At 1450°C and 1500°C (≥50% silicate melting), sulfide is virtually absent (largely dissolved as S in the silicate melt) and metallic melt spheres rim the charge.

In our experiments and chondrules [9], aggregate melting and surface tension effects can cause substantial migration and potentially nearly complete loss of metal at 50+% silicate partial melting. Higher degrees of silicate partial melting may be needed in gravitationally-dominated systems (e.g., asteroids).

Silicate Crystallization. These experiments provide insight into the crystallization of enstatite-rich melts. The silicate textures range from equigranular (≤1425°C) to extremely coarse-grained (1450°C) to spherulitic (1500°C), reflecting the effect of increasing temperature on the decreasing number of nuclei available for crystallization upon cooling. The 1425°C charge is texturally comparable to the Happy Canyon EC impact melt, while the Ilafegh 009 impact melt is comparable in grain size to the 1450°C charge, reflecting differing nuclei densities between these meteorites [10]. The coarse-grained aubrites likely crystallized from a melt with relatively few nuclei, perhaps even relatively rapid cooling rates.

Above 1400°C, minute (1–5 µm) Ca-rich sulfides occur in the silicate melt. Their presence seems to confirm the suggestion of [5] that S in the silicate melt will complex with Ca and crystallize oldhamite upon cooling. Controlled cooling runs are needed to test this idea.

References: [1] Lonsdale J. T. (1947) *Amer. Min.*, 32, 354–364. [2] Taylor G. J. *et al.* (1994) *Meteoritics*, 28, 34–52. [3] Watters T. R. and Prinz M. (1979) *Proc. LPSC Conf. 10th*, 1073–1093. [4] Casanova I. *et al.* (1994) *GCA*, 57, 675–682. [5] Fogel R. A. *et al.* (1996) *LPSC XXVII*, 371–372. [6] Dickinson T. L. *et al.* (1998) *Science*, submitted. [7] McCoy T. J. *et al.* (1998) *Meteoritics and Planet. Sci.*, submitted. [8] Keil K. (1968) *JGR*, 73, 6945–6976. [9] Zanda B. *et al.* (1994) *Science*, 265, 1846–1849. [10] McCoy T. J. *et al.* (1995) *GCA*, 59, 161–175.

HIGH SULFUR-LOW IRON SILICATE MELTS: LOW OXYGEN FUGACITY PHENOMENA OF IMPORTANCE TO AUBRITE FORMATION. R. A. Fogel, American Museum of Natural History, Department of Earth and Planetary Sciences, New York NY 10024 (bobby@amnh.org).

Introduction: E chondrites and aubrites are meteorite groups that formed under extreme degrees of reduction. The aubrites are thought to be low f_{O_2} melting products stemming from igneous activity on an E chondrite-like parent body [1]. Clouding a detailed understanding of aubrite formation is the poorly understood effects of low f_{O_2} on silicate and sulfide phase equilibria. Recent work has shown that sulfide and silicate igneous phase equilibria are intimately related under low f_{O_2} [2–4]. Under reducing conditions, sulfides can dissolve in appreciable (wt %) levels within silicate melts and sulfides may precipitate directly from the silicate melts [2–5].

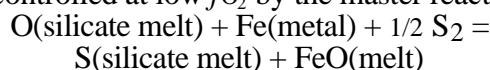
Melt FeO content is inversely related to S solubility under low f_{O_2} [2]; decreases in melt FeO lead to increases in S-solubility. In this relationship, FeO acts as a “pseudo-proxy” for f_{O_2} with decreasing f_{O_2} leading to decreases in melt FeO. Aubrite, pyroxenes and olivines contain little to no FeO [6], suggesting that f_{O_2} conditions were sufficiently low to make high-S silicate melts a hallmark of their formation. Additional experiments have been conducted, extending previous work [2], to further flesh out sulfide-silicate melt systematics.

Results: Equilibrium melting experiments (1250°–1400°C) of Indarch and Indarch+synthetic CaS starting compositions followed previously outlined procedures [2]. Additionally, several short duration runs (< 2 hrs) were conducted to minimize Na-loss and to gain insight into the approach to equilibrium.

Results of these experiments combined with those of [2] show a strong *hyperbolic* increase in S content of the melt with decreases in melt FeO (and f_{O_2}) (Figure). In one short duration experiment (1 atm), equilibrium f_{O_2} had not been achieved; the Si content of metal blebs running the length of the charge were internally homogenous, but varied in Si content from 0–7.5 wt %. The melt FeO-S systematics also recorded this disequilibrium and showed a sharp hyperbolic correlation of FeO and S within

the one experiment (Figure) that fall along the equilibrium Indarch melting line.

Discussion: The solubility of S in silicate melts and its relationship to melt FeO, is controlled at low f_{O_2} by the master reaction:



The equilibrium constant for this reaction is:

$$K = a_S \cdot a_{FeO} / (a_O \cdot a_{Fe} \cdot f_{S_2}^{1/2})$$

Setting $C = a_O \cdot a_{Fe} \cdot f_{S_2}^{1/2}$ and rearranging leads to:

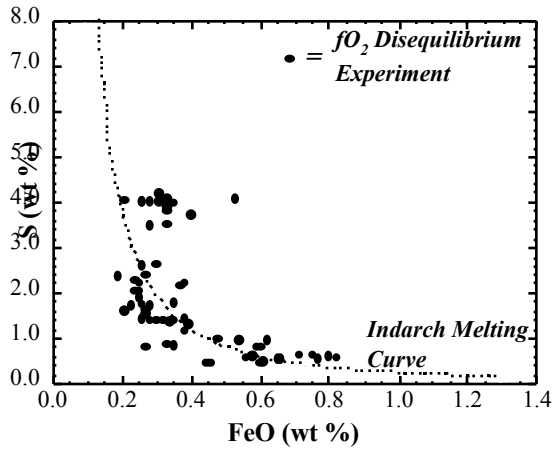
$$a_S = K \cdot C / a_{FeO}$$

This equation shows that for a constant a_O , f_{S_2} in the presence of excess Fe-metal, S-solubility should increase hyperbolically with decreases in FeO. This is confirmed both by the series of equilibrium experiments, and appears also to be the method by which equilibrium S solubility is approached.

Under low f_{O_2} , S dissolves in high concentrations within silicate melts by the formation of CaS^0 and MgS^0 melt units. The importance of this process is that the complexation of S with network modifying cations, such as Mg and Ca, removes these cations from the silicate network thereby changing the melts liquid line of descent and the phase equilibria of the cooling magma. All else being equal, an aubrite melt composition evolving at f_{O_2} diagnostic of aubrites will follow a different liquid line of descent and display differing phase equilibria, than a similar melt evolving at nominally higher f_{O_2} 's such as iron-wustite. For example, the tying up of Ca as CaS^0 units should decrease the anorthite component of plagioclase and suppress the crystallization of diopside from aubrite magmas [6] record extremely low FeO (< 0.02 to 0.16 wt %) contents for all aubrite enstatites, diopsides and forsterites. The K_D 's for forsterite, enstatite and diopside with basaltic liquids suggest that the melt will have a lower Mg# than the pyroxenes and olivine [e.g., 7]; however, calculations show that this would still lead to between a few hundred and a few thousand ppm FeO in the liquid. As shown in the figure, this FeO content predicts weight % levels of S

dissolved in the aubrite silicate liquid (Figure). The finding of weight % levels of S in aubrite basalt vitrophyre glasses [8] and melt inclusions in aubrites [9] confirm this prediction.

References: [1] Keil (1989) *Meteoritics*, 24, 195–208; [2] Fogel (1996) *LPSC XXVII*, 307–308; [3] McCoy et al., (1997) *LPSC XXVIII*, 903–904; [4] Dickinson et al. (1998) *LPSC XXIX*; [5] Fincham and Richardson (1954) *Proc. Roy. Soc. Lon.*, A 223, 40–62; [6] Watters and Prinz (1979) *Proc. Lunar Planet. Sci. X*, 1073–1093; [7] Longhi J. et al. (1978) *GCA*, 42, 1545–1558; [8] Fogel (1997) *LPSC XXVIII*, 369–370; [9] Fogel (1998) *LPSC XXIX*.



COMPLEXITIES ON THE ACAPULCOITE–LODRANITE PARENT BODY. C. Floss, McDonnell Center for the Space Sciences and Department of Earth and Planetary Sciences, Washington University, St. Louis MO 63130, USA (floss@howdy.wustl.edu).

Introduction: Recent studies have suggested that acapulcoites and lodranites are the products of complex partial melting and melt migration processes on a common parent body [1–3]. Preliminary trace-element data for several acapulcoites and lodranites [4] indicated that there are systematic differences between the groups. Specifically, pyroxenes in lodranites exhibit depletions of the rare earth elements (REE) and other incompatible trace elements, relative to acapulcoite pyroxenes, that are consistent with the formation and removal of silicate partial melts from the former. Furthermore, the trace-element characteristics of “transitional” EET 84302 [3] are more similar to those of acapulcoites than lodranites. In this work two additional meteorites from the acapulcoite–lodranite suite were studied. These new data indicate that the processes acting on the acapulcoite–lodranite parent body were more complex than those suggested by the initial study.

Results: Trace elements were measured by ion microprobe in ALHA 81187, an acapulcoite, and GRA 95209, which was recently classified as a lodranite [5]. Plagioclase REE abundances are similar in both meteorites ($\text{Nd} \sim 0.8 \times \text{CI}$), and are a factor of 4 higher than those reported for Acapulco and ALHA 81261, and a factor of 2 higher than in EET 84302 [4]. The pyroxenes also each have similar REE abundances in GRA 95209 and ALHA 81187 and, again, concentrations are high compared to those previously measured in acapulcoites. Clinopyroxene REE abundances, at $\text{Nd} \sim 15 \times \text{CI}$, are a factor of 2–3 higher than acapulcoite abundances, but are similar to those determined for EET 84302 clinopyroxene. Orthopyroxene REE abundances ($\text{Nd} \sim 0.15 \times \text{CI}$) are an order of magnitude higher than those determined for the acapulcoites and EET 84302. Although REE abundances are elevated in the pyroxenes, other incompatible-trace-element abundances are either similar to those observed in the acapulcoites (e.g., Ti in clino- and orthopyroxene) or intermediate between the acapulcoites and lodranites (e.g., Zr in clinopyroxene).

Apatite from acapulcoite ALHA 81187 has a REE pattern similar to other acapulcoite apatites and intermediate REE abundances [4]. No Ca-phosphates occur in the thin-section of GRA 95209 studied here, although they have been reported for other sections [6]. Instead, two Fe,Mn,Mg-bearing phosphates were observed [7].

Discussion: The similarity of trace-element abundances in the silicates from these two meteorites is unexpected, given the distinct depletions previously observed in lodranites relative to acapulcoites [4]. Furthermore, REE abundances are significantly higher than those previously noted for the “undepleted” acapulcoites. Graves Nunataks 95209, although classified as a lodranite, contains some plagioclase and is, in this respect, similar to EET 84302. Furthermore, acapulcoite ALHA 81187 contains less plagioclase than Acapulco and ALHA 81261 [2] and, like GRA 95209 and EET 84302, appears to be depleted in troilite relative to the chondritic abundances seen in most acapulcoites. These characteristics suggest that the bimodal classification of the acapulcoite–lodranite group is too simple. Evolution of the suite from “undepleted” acapulcoites to “depleted” lodranites may provide a better description of both mineralogical and geochemical data. Graves Nunataks 95209 and ALHA 81187 exhibit intermediate characteristics and appear to have experienced higher degrees of melting than “undepleted” acapulcoites, with resultant loss of troilite, and perhaps incipient silicate partial melting. The high REE abundances observed in the minerals of these meteorites may have resulted from melting of Ca-phosphates, with subsequent redistribution of the REE among the silicates.

References: [1] Mittlefehldt D. W. et al. (1996) *GCA*, 60, 867–882. [2] McCoy T. J. et al. (1996) *GCA*, 60, 2681–2708. [3] McCoy T. J. et al. (1997) *GCA*, 61, 623–637. [4] Floss C. (1998) in *LPS XXIX*, Abstract #1237. [5] Mason B. (1997) *Antarctic Met. News.*, 20, 1, 9. [6] McCoy T. J. and Carlson W. D. (1998) in *LPS XXIX*, Abstract #1675. [7] Floss C., this volume.

Introduction: The acapulcoite-lodranite clan of primitive achondrites provides us with a view of ultrametamorphism of chondritic parent bodies. Acapulcoites are highly metamorphosed chondritic materials, in which melting occurred in the Fe,Ni-FeS system, but probably not in the silicate system [1,2]. Lodranites experienced higher temperatures, including partial melting of the silicate system leaving basalt-depleted residues [2,3]. Some intermediate and hybrid members of this clan are also known. Migration of both the metal-sulfide and silicate melts appears to have been complex [2,4]. Study of new members of this clan will yield important information regarding the physics and chemistry of magmatism on asteroidal bodies early in solar system history. Here we present the preliminary results of our study of the new lodranite GRA 95209, and discuss its classification and the origin of the clan.

Petrology: GRA 95209 is a metal-rich stone containing regions of different textures and metal contents [5]. Our thin section contains regions of equigranular, relatively fine-grained (0.2-0.3 mm) silicates similar to acapulcoites, and regions with coarser grain size (0.6-1.0 mm) more similar to lodranites. GRA 95209 is relatively magnesian; average olivine is Fo_{92.6} with a molar Fe/Mn of 14.3. Average low- and high-Ca pyroxene compositions are Wo_{3.3}En_{89.5}Fs_{7.2} and Wo_{43.0}En_{53.5}Fs_{3.5} with molar Fe/Mn of 9.0 and 7.6. Plagioclase is Or_{1.8}Ab_{80.7}An_{17.5} in composition, similar to that in paired lodranites Y-791491, Y-791493 and acapulcoite ALHA81187 [2,3].

Geochemistry: We have performed INAA on splits from two samples of GRA 95209. One has Na/Sc, Sm/Sc, Sm/Yb and Eu/Yb like those of acapulcoites and is distinct from all other lodranites (e.g. Fig. 1). The lithophile element composition of this sample gives no evidence for loss of a silicate partial melt. The Ir/Ni ratio is slightly higher, and Se/Co slightly lower in this sample compared to most acapulcoites, consistent with some loss of a metal-sulfide partial melt. The second split has Na/Sc and Eu/Yb ratios like those of acapulcoites, but low Sm/Sc and Sm/Yb ratios, more like those of lodranites (Fig. 1). Its REE pattern similar to that of lodranite Y-8002 [6]. These characteristics may be consistent with either loss of a low degree silicate partial melt, or slight under-sampling of phosphates. These scenarios remain to be fully evaluated. Siderophile and chalcophile element data for this split are incomplete.

Discussion: The classification of acapulcoites and lodranites is based largely of petrographic criteria [1,3]. However, this clan is heterogeneous in textures, mineral compositions, O-isotopic compositions and bulk lithophile, siderophile and chalcophile element contents. This makes clear-cut classification difficult; EET 84302 is considered a transitional lodranite based on petrography, but is an acapulcoite based on bulk rock composition [2,3]. GRA 95209 is considered a lodranite based on petrography [5], but again, we find that the bulk rock composition is more similar to acapulcoites, and quite distinct from that of lodranites (Fig. 1). The lesson here may be that the acapulcoite-lodranite clan is too heterogeneous to allow simple pigeonholing of its members into distinct groups. We suggest that reevaluation of the classification of rock types in this clan is in order.

GRA 95209 appears to be ultrametamorphosed chondritic material, rather than a partial melt residue in the sense of lodranites. The silicate fraction of GRA 95209 shows no strong evidence for loss of a basaltic melt, in contrast to lodranites. Minor reduction in the Se/Co ratio could indicate some loss of a metal-sulfide melt, but less than we observed for EET 84302. This is curious in view of the petrographic evidence for extreme heterogeneous distribution of metal in GRA 95209 [5].

References: [1] McCoy et al. (1996) *GCA*, 60, 2681. [2] Mittlefehldt et al. (1996) *GCA*, 60, 867. [3] McCoy et al. (1997) *GCA*, 61, 623. [4] McCoy et al. (1997) *GCA*, 61, 639. [5] McCoy and Carlson (1998) *LPS XXIX*, Abstract #1675. [6] Torigoye et al. (1993) *Proc. NIPR Symp. Ant. Met.* 6, 100.

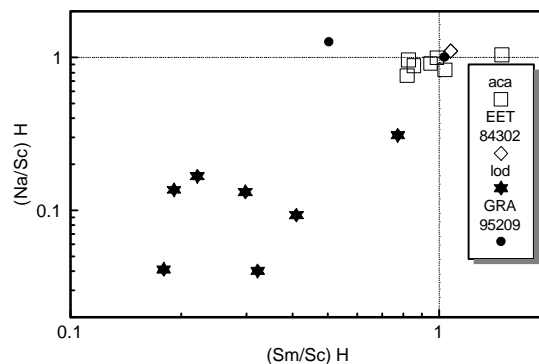


Fig. 1. H chondrite-normalized lithophile element ratios for acapulcoite-lodranite clan meteorites. Data are from this study and numerous literature sources.

ZINC CONTENTS OF UREILITE SILICATES. W. Klöck¹, K. Nakamura¹, M. Maetz², P. Arndt², ¹Institut für Geologische Wissenschaften, Universität Halle, Domstr.5, D-06108 Halle, Germany (kloeck@geologie.uni-halle.de), ²Max-Planck-Institut für Kernphysik, P.O. Box 103980, D-69029 Heidelberg, Germany

Bulk zinc abundances of ureilites are comparable to the zinc contents of CI-chondrites, but the distribution of zinc between different silicate mineral phases is not well known. Generally ureilites consist of euhe-dral olivines and pyroxenes with minor amounts of rare phases like chromite and daubreelite. In addition, they contain some metallic iron, either on grain boundaries between the silicates or as small inclusions predominantly in olivines.

Olivines and pyroxenes of several ureilite meteorite samples were analyzed using the PIXE facility in Heidelberg and the resulting data are compiled in Table 1. Major element compositions of the minerals were obtained by SEM-EDX and iron was used as an internal standard for the PIXE data reduction.

Olivines and pyroxenes of all ureilites, except Goalpara, contain between 100 and 500 ppm Zn. Generally Zn is higher in olivines compared to pyroxenes. In the Goalpara ureilite, however, olivines are much lower in Zn compared to pyroxenes. The levels of Zn in the silicates do in all cases agree with the bulk zinc data, except for Dyalpur, where the reported bulk zinc content is much lower compared to our PIXE data. Our present explanation for this discrepancy is a possible inhomogeneous distribution of Zn in this meteorite.

For comparison, three ordinary chondrite samples were analyzed, and as expected, silicates in these meteorites contain only minor amounts of zinc[1,2]. In ordinary chondrites, chromites were shown to be the host phases of Zn, whereas in the ureilites the silicates contain at least a major fraction of the bulk Zn-content. Chromites in Novo-Urei are very rare and contain on average about 0.8 wt% ZnO. We estimate that at least 90% of the bulk zinc content is contained in the silicates in the case of Novo-Urei. Zn contents of silicates and chromites are consistent with an estimated modal abundance of 20% pyroxenes and 80% olivines for the Goalpara ureilite.

The reason for the low levels of zinc in Goalpara olivines is not yet understood. The low Zn contents of the olivines explains the low bulk zinc content of 84 ppm compared to the bulk zinc content of 266 ppm for Novo-Urei[3]. Kenna, Novo-Urei and Dyalpur are weakly to moderately shocked samples, whereas Goalpara and Dar al Gani 084 experienced higher shock pressures and temperatures, as indicated by petrographic studies [4]. Bulk zinc contents of the more heavily shocked ureilites are lower compared to the

weakly shocked ureilites [3]. Therefore we assume that Zn might have been lost from the olivines by reheating caused by impact processes. Further studies should reveal if abundances of the volatile element zinc in meteoritic silicates can serve as an indicator for shock processes and the related thermal history of meteorites.

References: [1] Mason B. and Graham A.L. (1970) *Smithsonian Contributions to the Earth Sci.* **3**. [2] Allen R.O. and Mason B. (1973) *Geochim. et Cosmochim. Acta* **37**, 1435-1456. [3] Wasson J.T. et al., (1976) *Geochim. et Cosmochim. Acta* **40**, 1449-1458. [4] Goodrich C.A. (1992) *Meteoritics* **28**, 327-352.

Table 1. Zinc contents of ureilite silicates

	Goalpara		Kenna		Novo-Urei		Dyalpur		Dar al Gani 084	
	Oli	Px	Oli	Px	Oli	Px	Oli	Px	Oli	Px
Zinc (ppm)	10	310	280	210	270	220	540	330	240	90
Bulk zinc (ppm)	84		181		266		271			

IN SITU LASER MICROANALYSIS OF OXYGEN ISOTOPES IN UREILITES. G. J. MacPherson¹, R. D. Ash^{1,2}, and D. Rumble III², ¹Department of Mineral Sciences, MRC-119, National Museum of Natural History, Smithsonian Institution, Washington DC 20560, USA. ²Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Road NW, Washington DC 20015-1305, USA (glenn@glenm.si.edu).

Among the more enigmatic features of ureilites is the observation [1] that their bulk oxygen isotopic compositions as a group define a line of slope ~ 1 on a three-isotope O diagram, and this line is approximately the same as an ^{16}O -poor extension of the Allende CAI mixing line. This is generally taken to mean [1] that the ureilites are not related to each other by igneous processes within a single differentiated parent body, and that their bulk isotopic compositions are inherited from nebular rather than planetary processes, even though many features of these rocks indicate that they formed by igneous processes [e.g., 2,3, etc.]. Clayton and Mayeda [1] noted that members of the Group I (high Fe; [4]) ureilites appear to define 2 subgroups that differ from each other in $\Delta^{17}\text{O}$, and within each of which the oxygen isotopic data falls approximately along a slope- $1/2$ line on a three isotope diagram. More recent work has suggested that the Group I ureilites may consist of as many as four subgroups [5,6]

We analyzed individual mineral grains *in situ* within polished pristine slices of the Group I ureilites Kenna and Novo Urei, using the UV laser probe at the Carnegie Institution [7], and following SEM characterization of the slices. The beam diameter of the laser probe was approximately 400–500 μm . Precision of the data is better than 0.10‰ in $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$. Data for olivine and low-Ca pyroxene in each meteorite are given in Table 1, along with bulk data for the two meteorites from [1]. The Kenna olivine and pyroxene data are within analytical error of each other, although they appear to disperse along a line of slope close to $1/2$. Our mineral data for Kenna bracket the bulk meteorite composition in $\delta^{18}\text{O}$ but are slightly higher in (although within error of) $\delta^{17}\text{O}$ relative to bulk. The Novo Urei olivine and pyroxene points are clearly resolved from one another, with the pyroxene being higher in $\delta^{18}\text{O}$ by $\sim 0.3\text{‰}$ relative to the olivine. As with Kenna, the Novo Urei data define a line of low slope. The enrichment of pyroxene in ^{18}O relative to the olivine in Novo Urei is consistent in sign with igneous partitioning between the two

minerals. Unlike Kenna, our mineral data for Novo Urei do not bracket the bulk meteorite composition in $\delta^{18}\text{O}$ but rather are enriched in that isotope. It is likely that there is a ^{18}O -depleted phase (s) in Novo Urei not represented by our data. The Novo Urei mineral data are also slightly higher in $\delta^{17}\text{O}$ relative to bulk. For both meteorites, we attribute the displacement of our data by $\sim 0.1\text{‰}$ to higher $\delta^{17}\text{O}$ from the respective bulk compositions to systematic analytical differences between the Chicago and Carnegie labs. Weighted least-squares regression of combined mineral data for both meteorites gives a slope of 0.2712 ± 0.4346 , within error of a slope- $1/2$ (mass dependent fractionation) line.

The data thusfar are obviously limited and not conclusive, but are nonetheless entirely consistent with an igneous origin for both ureilites, possibly on the same parent body. This conclusion is consistent with the suggestion of Clayton and Mayeda [1] for these meteorites, but differs from that of [8] based on ion probe analyses of two Antarctic ureilites.

References: [1] Clayton R. N. and Mayeda T. K. (1988) *GCA*, 52, 1313. [2] Goodrich C. A. (1992) *Meteoritics*, 27, 327. [3] Walker D. and Grove T. (1993) *Meteoritics*, 28, 629. [4] Berkeley J. L. et al. (1980) *GCA*, 44, 1579. [5] Franchi I. A. et al. (1997) *Meteoritics & Planet. Sci.*, 32, A44. [6] Franchi I. A. et al. (1998) *LPS XXIX*. [7] Rumble D. III et al. (1997) *GCA*, 61, 4229. [8] Ruzicka A. et al. (1998) *LPS XXIX*.

TABLE 1.

	$\delta^{18}\text{O}$	$\delta^{17}\text{O}$	$\Delta^{17}\text{O}$
Novo Urei pyroxene	7.67	3.06	-0.93
Novo Urei olivine	7.34	2.97	-0.85
Kenna pyroxene	7.59	2.99	-0.96
Kenna olivine a	7.5	2.97	-0.93
Kenna olivine b	7.59	3.04	-0.91
Novo Urei bulk [1]	7.21	2.76	-0.99
Kenna bulk [1]	7.54	2.9	-1.02

OXYGEN ISOTOPE VARIATION IN THE BENCUBBIN METEORITE: AN EXOTIC COMPONENT IN THE MATRIX? I. A. Franchi, A. S. Sexton, and C. T. Pillinger, Planetary Sciences Research Institute, Open University, Milton Keynes MK7 6AA, UK (i.a.franchi@open.ac.uk).

Introduction: Bencubbin remains an enigmatic meteorite, being composed of subequal proportions of metal and silicate clasts together with a few chondritic clasts welded together with a shock melted matrix [1]. The silicate clasts are large broken fragments (up to 1.5 cm) and yet have chondritic textures and composition [2]. Models describing the origin of Bencubbin have problems accounting for many of these unusual features. The O isotopic composition of this meteorite is also somewhat unusual, the main silicate clast showing a similarity to CH and CR chondrites [4] and the chondritic clasts having quite different compositions [3]. This work is aimed at looking at the isotopic variation of the main silicate clasts and their relationship to the, so far neglected, matrix material.

Technique: The samples were broken from a slab of the meteorite with a small stainless steel chisel. The slab (50 × 15 × 5 mm), polished on one side, contained at least three distinct silicate clasts and considerable amounts of matrix material. Four samples each of the clasts and the matrix were obtained, weighing from 1 to 10mg. The samples were analysed using a laser fluorination technique [5].

Results and Discussion: The clast samples display a very narrow range in $\delta^{18}\text{O}$ around +1‰, although one sample does have a $\delta^{18}\text{O}$ value of -1‰ (fig) possibly due to incomplete fluorination of this sample. The $\Delta^{17}\text{O}$ value of the four clast samples is $-2.32 \pm 0.035\text{‰}$. This suggests that the clast samples represent a homogeneous reservoir. This is in contrast to the range of compositions displayed by chondrules from ordinary chondrites (OC) [6], clearly indicating some considerable differences in their formation. Alternatively, such isotopic homogeneity would be characteristic of large scale melting, perhaps associated with an impact origin [2].

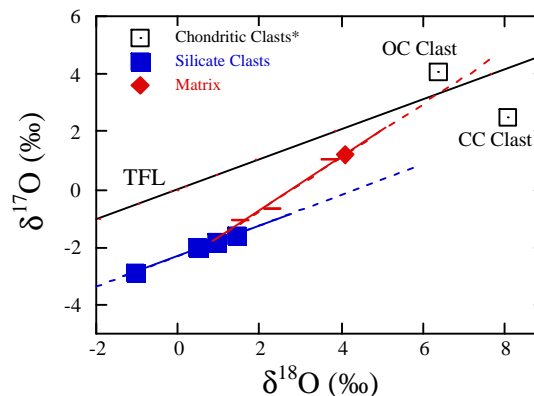
The four matrix samples extended the range of $\delta^{18}\text{O}$ values to over +4‰ and show a much wider range in $\Delta^{17}\text{O}$, with values up to -0.91‰. They appear to define a mixing line, one end member being the silicate clasts (fig). However, two of the matrix samples are strongly influenced by the other end-member component(s).

The two other O reservoirs so far identified in Bencubbin are the ordinary and carbonaceous chondrites [3]. The mixing line does not appear to be with either one of these components (Fig.), although a combination of the two could produce a suitable end

member. However, this would require that approximately 50% of the matrix was this chondritic component. This is unlikely as no such clasts were visible in the slab studied and they are generally very rare in the meteorite.

Chondrules from the CR chondrites have a very similar range of oxygen isotopic compositions to the Bencubbin matrix samples [4]. However there is no other evidence of any distinctive, relict CR chondrule material in Bencubbin.

An alternative mechanism to account for the observed mixing line may be for a small amount of a component with a more extreme O isotopic composition, possibly present in the regolith prior to the shock melting event or perhaps associated with the impact event. This possibility remains speculative but would at least allow the melt to be dominated volumetrically by the silicate clasts. Detailed investigation of compositional variation in the matrix should help constrain these possibilities.



Plot of O isotopic composition of silicate clasts and matrix in Bencubbin. *Data from [3].

References: [1] Lovering J. (1962) in *Researches on Meteorites* (C. B. Moore, ed.), [2] Weisberg M. K. et al. (1990) *Meteoritics*, 25, 269. [3] Clayton R. N. and Mayeda T. K. (1978) *GCA*, 42, 325. [4] Weisberg M. K. et al. (1995) *Proc. NIPR Symposium*, 8, 11. [5] Franchi I. A. et al. (1997) *LPSC XXVIII*, 379. [6] Bridges J. C. et al. (1998) *LPSC XXIX*, abstract #1401.

CONSTRAINTS ON THE FORMATION HISTORY OF BRACHINITES FROM RARE EARTH ELEMENT DISTRIBUTIONS. M. Wadhwa¹, J. Zipfel² and A. M. Davis³, ¹Department of Geology, The Field Museum, Roosevelt Rd. at Lake Shore Drive, Chicago, IL 60605, ²Max-Planck-Institut für Chemie, PO 3060, 55020 Mainz, Germany, ³Enrico Fermi Institute and Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637.

Introduction: The brachinite group of primitive achondrites is currently comprised of Brachina, Eagle's Nest, Hughes 026, Reid 013 and ALH84025. There is no consensus on how these igneous-textured, olivine-rich rocks (79–93 vol% olivine) were formed. While some authors favor a residual origin [1,2], others have suggested that the brachinites are cumulates [3–5]. In light of the 4564 Ma Mn-Cr age of Brachina [6], it is important to determine the petrogenesis of these meteorites, since this could place constraints on the earliest igneous processes on asteroids. With the aim of constraining their formation history, we have initiated a trace element study of the brachinites.

Experimental: Bulk chemical data for Hughes 026 and Reid 013, were obtained by INAA in Mainz. Minor and trace element abundances were measured in individual minerals in polished thin sections of Brachina, Hughes 026 and ALH84025 by ion microprobe in Chicago.

Results and Discussion: Hughes 026 has a bulk REE pattern that is LREE-enriched ($\text{La} \sim 2 \times \text{CI}$; $\text{La/Yb} \sim 5$). As has been suggested for Eagle's Nest [7], this LREE-enrichment is most likely the result of terrestrial weathering. In contrast, Reid 013 appears to be LREE-depleted (similar to ALH84025 [3]) and has the lowest REE abundances among the brachinites ($\text{La} \sim 0.06 \times \text{CI}$).

Hughes 026 and Reid 013 have bulk depletions in Na and K (by a factor of ~ 10 relative to CI), indicating depletion in plagioclase similar to that in ALH84025 [3] and Eagle's Nest [7]. We note that among the brachinites, Brachina is exceptional in its near-chondritic lithophile element abundances. Also, Hughes 026 is exceptional in its significant depletion in Ir ($0.02 \times \text{CI}$) and Ni ($0.03 \times \text{CI}$).

In Brachina, ion microprobe analyses show homogeneous distributions of REEs in all minerals. Apatite has an LREE-enriched pattern ($\text{La} \sim 70 \times \text{CI}$; $\text{La/Yb} \sim 4$) with a small negative Eu anomaly ($\text{Eu/Eu}^* \sim 0.75$). Plagioclase is also LREE-enriched ($\text{La} \sim 2.5 \times \text{CI}$; $\text{La/Dy} \sim 8$) and has the characteristic positive Eu anomaly ($\text{Eu/Eu}^* \sim 6$). Augite has an LREE-depleted pattern ($\text{La} \sim 3.5 \times \text{CI}$; $\text{La/Yb} \sim 0.5$) and moderate Eu anomaly ($\text{Eu/Eu}^* \sim 0.5$). Olivine has low REE abundances, but its REE pattern is V-shaped, which we interpret as resulting from terrestrial weathering.

In Hughes 026, we analyzed apatite, augite and olivine; no plagioclase was found. As in Brachina, apatite has an LREE-enriched pattern, but REE abundances are lower than in Brachina ($\text{La} \sim 13\text{--}42 \times \text{CI}$). One of the augite grains analyzed has an LREE-depleted pattern ($\text{La} \sim 0.4 \times \text{CI}$; $\text{La/Yb} \sim 0.1$), but another has a V-shaped REE pattern, most likely from terrestrial weathering. Olivine may be unaffected by such weathering, as it has an LREE-depleted pattern ($\text{La} \sim 0.02 \times \text{CI}$; $\text{La/Yb} \sim 0.04$).

In ALH84025, we analyzed augite and olivine. We also measured a small ($\sim 15 \mu\text{m}$) whitlockite grain, the only Ca phosphate we could locate; no plagioclase was found. Augite is LREE-depleted ($\text{La} \sim 0.3 \times \text{CI}$; $\text{La/Yb} \sim 0.07$), while the olivine has very low REE abundances ($\text{La} < 0.01 \times \text{CI}$) and a steep LREE-depleted pattern ($\text{La/Yb} < 0.02$). Therefore, the LREE depletion in the ALH84025 bulk rock [3] is because augite and olivine are the main carriers of REEs (whitlockite does not contribute significantly owing to its small abundance and low REE concentrations). We did not find any carrier for the positive Eu anomaly noted by [3] in the ALH84025 bulk rock.

Of the three brachinites in which REE microdistributions were measured, ALH84025 appears to be least affected by weathering, while Hughes 026 is most weathered (supported by LREE-enrichment in its bulk rock REE pattern). Brachina may have been mildly weathered, so that only olivine was affected. REE microdistributions in Brachina and ALH84025 are consistent with extensive reequilibration and homogenization. If these rocks are cumulates, the signature of fractional crystallization was not preserved in the REE distributions in augite. Further analyses of the most differentiated (and possibly least weathered) samples, ALH84025 and Reid 013, will be required to better evaluate whether or not these samples may be of cumulate or residual origin.

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BRACHINITES: RESIDUES FROM LOW DEGREES OF MELTING OF A HETEROGENEOUS PARENT BODY. C. A. Goodrich, Max-Planck-Institut für Chemie, P.O. 3060, 55020 Mainz, Germany (goodrich@mpch-mainz.mpg.de).

Introduction: Brachinites are a small group of primitive achondrites (Brachina, ALH 84025, Eagle's Nest, Hughes 026, and Reid 013/Nova 003) distinguished by common mineralogy (olivine + augite \pm plagioclase \pm orthopyroxene) and relatively Fe-rich olivine (Fo ~65–68). Brachina is a fine-grained (0.1–0.3 mm) equigranular assemblage of 5–9% augite, 10–11% plagioclase, and a trace of orthopyroxene [1,2], and has a nearly flat REE pattern at $\sim 2 \times \text{CI}$ [3]. It was interpreted by [2] to be an almost primitive meteorite that experienced only a small amount of melting. In contrast, ALH 84025 is coarser-grained (up to 2.7 mm) with prismatic olivine shapes, and contains only olivine + 4.2–15% augite [3]. It has a LREE-depleted pattern with La $\sim 0.28 \times \text{CI}$ and Lu $\sim 0.65 \times \text{CI}$ [3]. Eagle's Nest is similarly coarse-grained, and contains only olivine + $\sim 7\%$ augite [4]. Warren and Kallemeyn [3] suggested that both ALH 84025 and Brachina are cumulates.

Wadhwa et al. [5] studied the ^{53}Mn - ^{53}Cr system of Brachina and found that ^{53}Mn ($t_{1/2} = 3.7$ Ma) was alive at the time of the last Cr isotopic equilibration in this meteorite. Relative to the angrite LEW 86010, they obtained an age of 4563.7 ± 0.9 Ma, ~ 2 Ma younger than CAIs [6]. This extremely old age seems easy to reconcile with the interpretation that Brachina is a residue of a very small amount of melting. However, if brachinites are cumulates, a more extensive igneous history would be required, and this age would be much more remarkable.

Here I present results of equilibrium partial melting calculations designed to determine whether brachinites can be modeled as simple residues of low degrees of melting of chondritic material. I focus initially on Brachina, ALH 84025 and Eagle's Nest.

Method: Calculations were performed using MAGPOX [7] at 10 b pressure. I assumed that FeO content was a free parameter and could be adjusted to produce the desired mg for residual olivine. This assumption is justified under the hypothesis that both the total Fe and oxidized Fe contents of the precursor materials of all primitive achondrites were determined by nebular processes [8].

Results: A Brachina-like residue can be produced by 1–2% melting of material having Ca/Al = CI, Si/Mg at the high end of the CC range, and alkali contents at the high end of the CC range (necessary to ensure that the low-Ca pyroxene is orthopyroxene rather than pigeonite), if Ca/Mg and Al/Mg are ele-

vated to $\sim 1.7 \times \text{CI}$. Such material could be produced by addition of $\sim 1.5\%$ of 1500°K high-temperature condensate (HTC [9]) to an average CC composition.

This material could not, however, also yield ALH 84025- and Eagle's Nest-like residues (olivine + 7–9% augite, assuming a mean for ALH 84025). Starting materials with superchondritic Ca/Al are required to produce such residues. For example, an average CC composition with high alkali contents and Ca/Al increased to $\sim 1.5 \times \text{CI}$ (which can be achieved by subtraction of $\sim 0.7\%$ corundum) could produce an olivine-augite residue with $\sim 8\%$ augite at 9–11% melting (which is consistent with the Lu depletion in ALH 84025 assuming that original REE abundances were $\sim 2 \times \text{CI}$).

Discussion: These calculations suggest that Brachina, ALH 84025 and Eagle's Nest could have originated as residues of low degrees of melting (1–10%) of materials which showed small deviations (in Si/Mg, Ca/Al and Ca/Mg) from the range of known CC compositions. These deviations can be attributed to nebular fractionation processes such as excess accretion of $\sim 1.5\%$ HTC and incomplete accretion of $\sim 0.7\%$ corundum. These degrees of fractionation do not seem implausible, particularly in light of the much larger nebular fractionations postulated for precursor materials of angrites [10] and ureilites [11]. Thus, it is not necessary to invoke extensive igneous events such as large-scale melting and fractional crystallization in the ~ 2 Ma [5] between formation of CAIs and formation of Brachina.

Furthermore, these calculations indicate that if Brachina, ALH 84025 and Eagle's Nest are derived from a single parent body, then that body was heterogeneous in major element composition to a greater degree than chondrites, and was not homogenized by melting.

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RARE-EARTH-ELEMENT ABUNDANCE OF PYROXENE AND PLAGIOCLASE IN A PRISTINE EUCRITIC BASALT, YAMATO 75011,84. T. Arai¹, H. Takeda², J. J. Papike³, C. K. Shearer³, and M. Miyamoto¹, ¹Mineralogical Institute, Graduate School of Science, University of Tokyo, Hongo, Tokyo 113-0033, Japan, ²Research Institute, Chiba Institute of Technology, Tsudanuma, Narashino, Chiba 275-0016, Japan, ³Institute of Meteoritics, Department of Earth and Planetary Science, University of New Mexico, Albuquerque NM 87131-1126, USA.

Introduction: Eucrite basalts are products of the earliest planetary volcanism in the solar system. However, they generally suffered from brecciation and metamorphism on the parent body [e.g., 1] and thus their mineral chemistries and crystallization ages tend to be reset [e.g., 1,2]. Yamato (Y) 75011,84 is a basaltic clast in a polymict breccia and rarely preserves its primary texture, mineral composition, and crystallization age [3]. We analyzed REE abundance of pyroxene and plagioclase by ion microprobe and ensured its pristinity by comparing the REE abundance of the bulk clast with that of the parent magma calculated from the mineral compositions.

We investigated Y 75011,84 eucrite basalt from NIPR by chemical map analysis and analyzed REE of the spots of the earliest crystallization by the Cameca IMS 4f instrument operated by the University of New Mexico/Sandia National Laboratories Ion Microprobe Facilities.

Results and Discussion: Average REE abundance of pyroxenes and plagioclases is compared with bulk-clast REE abundance in Fig.1. All pyroxene cores from four zoned pyroxenes show almost identical abundances for HREE, although the LREE are scattered due to their extremely low concentration. Although analyses of Eu for all cores fall below detection limit, all have negative Eu anomaly. Two plagioclase grains were analyzed and their REE abundances are similar to each other, except Er and Yb. Pun and Papike [4] analyzed pyroxene cores from probably a similar clast (Y 75011,96) as Y 75011,84. However, REE abundances of

their cores are ~2–4 higher than that of our cores. This suggests that pyroxene cores in Y 75011,84 could be more primitive and more likely preserve compositions of a primary magma.

REE abundance of a parent magma was calculated from average REE abundances of pyroxenes and plagioclases, using partition coefficient *D* of McKay et al. [5] and Phinney and Morrison [6] respectively. Both calculated parent melts have REE abundance of ~20–30 CI chondrite and a fairly flat pattern, which well matches the bulk-clast REE abundance by Palme and Ikeda (1994, personal communication). This strongly supports a fact that cores of pyroxene and plagioclase in Y 75011,84 clast record the REE compositions of the parent magma.

The REE abundance of the parent magma for Y 75011,84 eucrite basalt is higher than those for REE-enriched ordinary eucrites, such as Nuevo Laredo and Stannern [7]. The flat REE pattern despite the highly enriched REE abundance, can be explained by the co-crystallization of pyroxene and plagioclase from the melt, in which REE abundance of the two minerals have complimentary trends.

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Fe-Ni METAL BEARING UNIQUE EUCRITE EET92023: ITS PETROGRAPHY, SIDERO-PHILE CONCENTRATIONS AND PETROGENEIS. K. Kaneda¹ and P. H. Warren², ¹Mineralogical Institute, Graduate School of Science, University of Tokyo, 113-0033, Japan, ²Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA.

EET92023 is a cumulate eucrite that superficially resembles Moore County. Mittlefehldt et al. [1] used INAA to determine that it has extraordinarily high siderophile concentrations, and tentatively suggested that it might be a clast from a mesosiderite. We have studied its texture and mineralogy, and used INAA and RNAA to determine a larger suite of siderophile elements.

The mode is 59.1% pyroxene, 38.9% plagioclase, 0.8% troilite, 0.5% Fe-Ni metal, 0.5% silica, plus minor phosphate, chromite and ilmenite. Metal grains, up to ~300 μm in diameter, are consistently anhedral and equigranular, unlike the metals of mesosiderites, which are chaotically xenomorphic. Fe-Ni metals are mainly divided into two phases, low Ni phase (kamacite) and high Ni phase (taenite), as in ordinary chondrites and iron meteorites. Taenite grains show strong chemical zoning. From core to rim, Ni contents increase from ~39 to ~54 wt%, often with a compositional discontinuity near grain edges. This discontinuity might be related to a change of texture, from cloudy interior to outer taenite rim (OTR) [2]. High Ni contents (> about 48 wt%) of the rims and the possible presence of OTR suggest they may be tetrataenite.

Because the boundary between kamacite and taenite is sharp and linear, a planar diffusion model was applied to the Ni zoning profile in taenite to estimate the approximate cooling rate of Fe-Ni metal. Calcium-phosphates (apatite and whitlockite) are scattered in this thin section, so the modeling included the effect of P on diffusion coefficients [3]. The phase diagram adopted in this work [4] was determined by investigation of metal phases in meteorites. Calculated cooling rate of Fe-Ni metal in EET92023 is ~4°C/My from ~700°C to ~300°C.

Although the profiles of Fe-Ni metal indicate very slow cooling, by eucrite standards, other textures observed in EET92023 suggest that cooling was fast, by cumulate eucrite standards. Augite exsolution lamellae in pyroxenes are fairly thin (generally <0.5 μm , spaced several micrometers apart). Pyroxenes are commonly zoned. Small pyroxenes (<~300 μm in diameter) have constant mg [$\text{Mg}/(\text{Mg} + \text{Fe})$] at ~0.51, but in larger pyroxenes mg decreases from core (0.58) to rim (0.51). Larger grains also show Ca zonation, with augite exsolution lamellae increasing in

thickness toward the rim. Some rims even give way to discrete augite and low-Ca pyroxene dominated regions (50–100 μm across), possibly produced as primary-igneous (not exsolved) augite + low-Ca pyroxene. Plagioclases are typically rectangular with rounded edges, and retain traces of euhedral Ca-rich (~An95) cores. Relatively Na rich rims (An80–68) partly cover euhedral ~ subhedral plagioclases.

Our analyses of two powder samples from a 600-mg chip confirm a strong bulk-compositional similarity to Moore County, except for siderophile elements. The siderophile contrast is even more dramatic than suggested by [1], who reported results in terms of EET92023/MC ratios, e.g., Ir = 100 \times . Our results (averaged, in $\mu\text{g/g}$) for Ni, Ge, Re, Os, Ir and Au are 1230, 1.41, 0.0053, 0.046, 0.050 and 0.015. Expressed as an EET92023/MC ratios, the Os result is 15000 \times . These data hint at possible kinship with mesosiderites, because CI-normalized Re/Ir (1.33 \times) and Ge/Ir (0.40 \times) resemble, in dampened form, similar fractionations in mesosiderites.

This eucrite should not be classified as a normal cumulate eucrite, because well-preserved zoning trends and weakly developed pyroxene exsolution structures indicate comparatively rapid near-solidus cooling, while the high FeNi-metal and siderophile abundances suggest origin from an impact melt. The slower cooling from ~700°C to ~300°C inferred from taenite zoning suggests that the rock was relocated to a slower-cooling environment while still at roughly 700°C. This transition might have been caused by burial under impact ejecta, or possibly, if the mesosiderite clast model is correct, by involvement in a general reheating of mesosideritic materials at ≥ 4.47 Ga, or localized reheating at 4.5–3.9 Ga [5]. However, the FeNi-metal and siderophile enrichments and fractionated Ge/Ir and Re/Ir ratios (i.e., the only evidence for possible mesosiderite kinship) must date from the initial igneous crystallization of EET92023.

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HOWARDITE-EUCRITE-DIOGENITE MAGMA OCEAN PETROGENESIS: EQUILIBRIUM OR FRACTIONAL CRYSTALLIZATION? P. H. Warren, Institute of Geophysics and Planetary Physics, University of California–Los Angeles, Los Angeles CA 90095-1567, USA (pwarren@ucla.edu).

Richter and Drake [1] recently adduced evidence from siderophile element partitioning supporting the hypothesis that core formation on the HED parent asteroid occurred at very high temperature, implying (or confirming) the existence of a primordial magma ocean. These same authors also proposed [2] that crystallization of the HED magma ocean (MO) was an equilibrium process for all but the final 20% of the solidification. The model assumes that at 80% solidification “convective lockup” finally caused crystal settling. The MO then adjusted itself into a layer of solid diogenite and residual melt, which soon solidified into the eucritic crust. The equilibrium premise of this model seems implausible. Actually, although Richter and Drake label and model their scenario as equilibrium, their discussion invokes “initial” formation of a small volume of dunite below the diogenites, in a deviation from true equilibrium solidification.

The physical arguments cited for equilibrium crystallization are oversimplified. Turbulent convective flow is supposed to keep all crystals suspended in the melt up to 80% MO crystallization. Convective vigor is modeled based on a form of the Rayleigh equation with $Ra \propto D^5$, but this form applies only to systems with major active heat sources. The MO may have melted via internal heating, but during its crystallization the primordial heat source (^{26}Al ?) might easily have become negligible. The more general form of the Rayleigh equation has $Ra \propto D^3$ — a whopping difference. The model ignores the potential for large suspended crystal fractions to create regional compositional (clustered crystals vs. melt) buoyancy forces that, given realistic assumptions about convection complexity (layering, unsteadiness of flow), can easily overwhelm the thermal convective force, even at crystal fraction of <0.03 [3].

One of the most fundamental, basic, defining characteristics of diogenites is their tendency to be almost monomineralic orthopyroxenite. Conveniently, Bowman et al. [4] have just published modes for 20 diogenites (I regard several presumptive pairs as single meteorites). The average mode is $94 \pm 9\%$ pyroxene, $2.5 \pm 8\%$ olivine and $1.3 \pm 4\%$ silica. Excluding two oddballs rich in either olivine or silica, the means are $94.8 \pm 3.7\%$ pyroxene, $0.8 \pm 1.3\%$ olivine and $0.4 \pm 0.3\%$ silica. Literature modes for numerous additional diogenites are uniformly close to this average. It seems

clear that the overall olivine/pyroxene volume ratio for diogenites is <0.3 and vastly less than 1.

Equilibrium crystallization requires that all crystals remain in constant close proximity to the residual melt. This may in principle be achieved by convective stirring, but it implies that the crystal proportions are uniform throughout the system; the olivine/pyroxene ratio is as high at the top of the MO as at the bottom. The olivine/pyroxene ratio at 80% solidification (o/p_{80}) will depend on the initial MO composition (i.e., essentially the bulk-silicate composition of the asteroid). For the bulk composition assumed, o/p_{80} is 1.19 (by mass; from Fig. 6 of [2]), i.e., grossly inconsistent with the olivine/pyroxene ratio of diogenites. Alternative initial compositions could in principle yield an $o/p_{80} \ll 1$, but the only primitive materials with much lower olivine/pyroxene than the composition modeled are enstatite chondrites, which are far too low in FeO/MgO to be related to eucrites. In general, primitive materials have uniform MgO/SiO₂. A type with low enough olivine/pyroxene and yet high enough FeO/MgO to satisfy the demands of the equilibrium MO model probably does not exist.

A key advantage claimed for the equilibrium MO model over fractional crystallization models [e.g., 5, 6, 7], is that fractional crystallization tends to predict implausibly high FeO in the late-stage melts that both models stipulate played a key role in genesis of the eucrites. The main problem with this argument is that the MO was almost certainly not a simple closed system. Primitive, high MgO/FeO material was probably accreting into it from space, and it may well have been periodically replenished with primitive melt from a deep layer of the asteroid that avoided total involvement in the initial MO. But this notion of open-system behavior of the HED asteroid’s MO is not new [8].

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PARTIAL MELTING OF THE INDARCH (EH4) METEORITE: A TEXTURAL VIEW OF MELTING AND MELT MIGRATION. T. J. McCoy¹, T. L. Dickinson², and G. E. Lofgren^{3,1} Department of Mineral Sciences, MRC 119, Smithsonian Institution, Washington DC 20560, USA (mccoy.tim@nmnh.si.edu), ²National Science Foundation, 4201 Wilson Boulevard, Arlington VA 22230, USA, ³Code SN2, NASA Johnson Space Center, Houston TX 77058, USA.

Introduction: Aubrites are breccias composed of FeO-free, mafic silicates, plagioclase, Si-bearing metal, and unusual sulfides (e.g., oldhamite, alabandite). Textural features [1–4] suggest a prolonged thermal history with high degrees of partial melting, melt migration, crystallization and slow cooling. Experimental studies [5,6] have not focused on textural and melt migration features. We have conducted experiments on the Indarch (EH4) enstatite chondrite and emphasizing textural aspects of melting and melt migration, and implications for melt crystallization [7].

Experimental Technique: A detailed description of the experimental technique is given in [6]. Each experiment utilized ~160 mg of powdered Indarch, producing charges ~5 mm in diameter. Solid metal buffers (Cr,V) were used in combination with graphite crucibles to maintain the appropriately low oxygen fugacity. Charges were sealed in evacuated silica tubes and run at 1000°–1500°C for 4–24 hrs. Phase identification was confirmed with the electron microprobe. Modal analyses of 400–650 points/charge were conducted.

Results and Discussions: We discuss silicate melting and sintering, metal-sulfide melt segregation, and implications for the crystallization of these melts.

Silicate Melting and Sintering. Indarch silicates include enstatite, plagioclase, free SiO₂ and FeO-bearing pyroxene [6,8]. Silicate melting begins at 1100°C and plagioclase, SiO₂ and FeO-rich pyroxene are exhausted by 1200°C (~9% silicate melting). The degree of silicate partial melting increases with temperature, and forsterite crystallization is observed at 1400°–1450°C. At 1500°C, silicates are completely melted.

The 1000°C charge contains ~50% void space. The 1200°C exhibits ~10 vol% silicate partial melting and only ~35 vol% void space, producing a coherent charge. By 1400°C, silicate partial melting has reached ~20%, the charge is spherical with no appreciable void space, and enstatite grains have coarsened from ~100 µm to ~300 µm. Limited melt migration is observed at 1425°C. At 1500°C, the charge is completely melted.

Metal Melting and Segregation. All of the metal and sulfide phases melt by 1000°C, suggesting they all participate in melting at the Fe,Ni-FeS cotectic (988°C). At 1000°C, each of non-silicate melt

components occur as distinct, small (~10 µm), irregular grains throughout the charge. At 1200°–1425°C, the metal is intergrown FeNiSi and C-bearing metal. At 1400°–1425°C (~25% silicate melting), large compound (≤3 mm) metal-sulfide spheres are present. At 1450°C and 1500°C (≥50% silicate melting), sulfide is virtually absent (largely dissolved as S in the silicate melt) and metallic melt spheres rim the charge.

In our experiments and chondrules [9], aggregate melting and surface tension effects can cause substantial migration and potentially nearly complete loss of metal at 50+% silicate partial melting. Higher degrees of silicate partial melting may be needed in gravitationally-dominated systems (e.g., asteroids).

Silicate Crystallization. These experiments provide insight into the crystallization of enstatite-rich melts. The silicate textures range from equigranular (≤1425°C) to extremely coarse-grained (1450°C) to spherulitic (1500°C), reflecting the effect of increasing temperature on the decreasing number of nuclei available for crystallization upon cooling. The 1425°C charge is texturally comparable to the Happy Canyon EC impact melt, while the Ilafegh 009 impact melt is comparable in grain size to the 1450°C charge, reflecting differing nuclei densities between these meteorites [10]. The coarse-grained aubrites likely crystallized from a melt with relatively few nuclei, perhaps even relatively rapid cooling rates.

Above 1400°C, minute (1–5 µm) Ca-rich sulfides occur in the silicate melt. Their presence seems to confirm the suggestion of [5] that S in the silicate melt will complex with Ca and crystallize oldhamite upon cooling. Controlled cooling runs are needed to test this idea.

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HIGH SULFUR-LOW IRON SILICATE MELTS: LOW OXYGEN FUGACITY PHENOMENA OF IMPORTANCE TO AUBRITE FORMATION. R. A. Fogel, American Museum of Natural History, Department of Earth and Planetary Sciences, New York NY 10024 (bobby@amnh.org).

Introduction: E chondrites and aubrites are meteorite groups that formed under extreme degrees of reduction. The aubrites are thought to be low f_{O_2} melting products stemming from igneous activity on an E chondrite-like parent body [1]. Clouding a detailed understanding of aubrite formation is the poorly understood effects of low f_{O_2} on silicate and sulfide phase equilibria. Recent work has shown that sulfide and silicate igneous phase equilibria are intimately related under low f_{O_2} [2–4]. Under reducing conditions, sulfides can dissolve in appreciable (wt %) levels within silicate melts and sulfides may precipitate directly from the silicate melts [2–5].

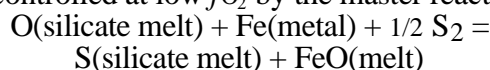
Melt FeO content is inversely related to S solubility under low f_{O_2} [2]; decreases in melt FeO lead to increases in S-solubility. In this relationship, FeO acts as a “pseudo-proxy” for f_{O_2} with decreasing f_{O_2} leading to decreases in melt FeO. Aubrite, pyroxenes and olivines contain little to no FeO [6], suggesting that f_{O_2} conditions were sufficiently low to make high-S silicate melts a hallmark of their formation. Additional experiments have been conducted, extending previous work [2], to further flesh out sulfide-silicate melt systematics.

Results: Equilibrium melting experiments (1250°–1400°C) of Indarch and Indarch+synthetic CaS starting compositions followed previously outlined procedures [2]. Additionally, several short duration runs (< 2 hrs) were conducted to minimize Na-loss and to gain insight into the approach to equilibrium.

Results of these experiments combined with those of [2] show a strong *hyperbolic* increase in S content of the melt with decreases in melt FeO (and f_{O_2}) (Figure). In one short duration experiment (1 atm), equilibrium f_{O_2} had not been achieved; the Si content of metal blebs running the length of the charge were internally homogenous, but varied in Si content from 0–7.5 wt %. The melt FeO-S systematics also recorded this disequilibrium and showed a sharp hyperbolic correlation of FeO and S within

the one experiment (Figure) that fall along the equilibrium Indarch melting line.

Discussion: The solubility of S in silicate melts and its relationship to melt FeO, is controlled at low f_{O_2} by the master reaction:



The equilibrium constant for this reaction is:

$$K = a_S \cdot a_{FeO} / (a_O \cdot a_{Fe} \cdot f_{S_2}^{1/2})$$

Setting $C = a_O \cdot a_{Fe} \cdot f_{S_2}^{1/2}$ and rearranging leads to:

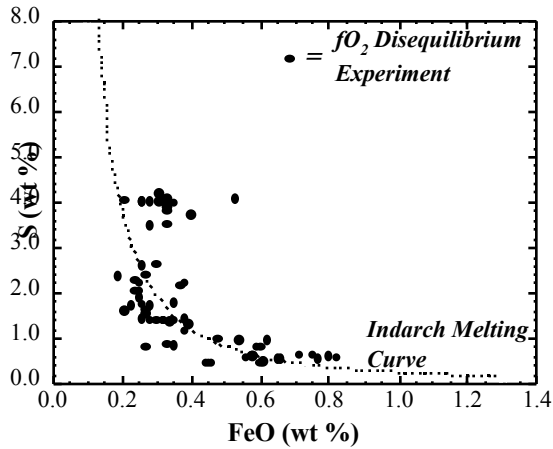
$$a_S = K \cdot C / a_{FeO}$$

This equation shows that for a constant a_O , f_{S_2} in the presence of excess Fe-metal, S-solubility should increase hyperbolically with decreases in FeO. This is confirmed both by the series of equilibrium experiments, and appears also to be the method by which equilibrium S solubility is approached.

Under low f_{O_2} , S dissolves in high concentrations within silicate melts by the formation of CaS^0 and MgS^0 melt units. The importance of this process is that the complexation of S with network modifying cations, such as Mg and Ca, removes these cations from the silicate network thereby changing the melts liquid line of descent and the phase equilibria of the cooling magma. All else being equal, an aubrite melt composition evolving at f_{O_2} diagnostic of aubrites will follow a different liquid line of descent and display differing phase equilibria, than a similar melt evolving at nominally higher f_{O_2} 's such as iron-wustite. For example, the tying up of Ca as CaS^0 units should decrease the anorthite component of plagioclase and suppress the crystallization of diopside from aubrite magmas [6] record extremely low FeO (< 0.02 to 0.16 wt %) contents for all aubrite enstatites, diopsides and forsterites. The K_D 's for forsterite, enstatite and diopside with basaltic liquids suggest that the melt will have a lower Mg# than the pyroxenes and olivine [e.g., 7]; however, calculations show that this would still lead to between a few hundred and a few thousand ppm FeO in the liquid. As shown in the figure, this FeO content predicts weight % levels of S

dissolved in the aubrite silicate liquid (Figure). The finding of weight % levels of S in aubrite basalt vitrophyre glasses [8] and melt inclusions in aubrites [9] confirm this prediction.

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Introduction: Recent studies have suggested that acapulcoites and lodranites are the products of complex partial melting and melt migration processes on a common parent body [1–3]. Preliminary trace-element data for several acapulcoites and lodranites [4] indicated that there are systematic differences between the groups. Specifically, pyroxenes in lodranites exhibit depletions of the rare earth elements (REE) and other incompatible trace elements, relative to acapulcoite pyroxenes, that are consistent with the formation and removal of silicate partial melts from the former. Furthermore, the trace-element characteristics of “transitional” EET 84302 [3] are more similar to those of acapulcoites than lodranites. In this work two additional meteorites from the acapulcoite–lodranite suite were studied. These new data indicate that the processes acting on the acapulcoite–lodranite parent body were more complex than those suggested by the initial study.

Results: Trace elements were measured by ion microprobe in ALHA 81187, an acapulcoite, and GRA 95209, which was recently classified as a lodranite [5]. Plagioclase REE abundances are similar in both meteorites ($\text{Nd} \sim 0.8 \times \text{CI}$), and are a factor of 4 higher than those reported for Acapulco and ALHA 81261, and a factor of 2 higher than in EET 84302 [4]. The pyroxenes also each have similar REE abundances in GRA 95209 and ALHA 81187 and, again, concentrations are high compared to those previously measured in acapulcoites. Clinopyroxene REE abundances, at $\text{Nd} \sim 15 \times \text{CI}$, are a factor of 2–3 higher than acapulcoite abundances, but are similar to those determined for EET 84302 clinopyroxene. Orthopyroxene REE abundances ($\text{Nd} \sim 0.15 \times \text{CI}$) are an order of magnitude higher than those determined for the acapulcoites and EET 84302. Although REE abundances are elevated in the pyroxenes, other incompatible-trace-element abundances are either similar to those observed in the acapulcoites (e.g., Ti in clino- and orthopyroxene) or intermediate between the acapulcoites and lodranites (e.g., Zr in clinopyroxene).

Apatite from acapulcoite ALHA 81187 has a REE pattern similar to other acapulcoite apatites and intermediate REE abundances [4]. No Ca-phosphates occur in the thin-section of GRA 95209 studied here, although they have been reported for other sections [6]. Instead, two Fe,Mn,Mg-bearing phosphates were observed [7].

Discussion: The similarity of trace-element abundances in the silicates from these two meteorites is unexpected, given the distinct depletions previously observed in lodranites relative to acapulcoites [4]. Furthermore, REE abundances are significantly higher than those previously noted for the “undepleted” acapulcoites. Graves Nunataks 95209, although classified as a lodranite, contains some plagioclase and is, in this respect, similar to EET 84302. Furthermore, acapulcoite ALHA 81187 contains less plagioclase than Acapulco and ALHA 81261 [2] and, like GRA 95209 and EET 84302, appears to be depleted in troilite relative to the chondritic abundances seen in most acapulcoites. These characteristics suggest that the bimodal classification of the acapulcoite–lodranite group is too simple. Evolution of the suite from “undepleted” acapulcoites to “depleted” lodranites may provide a better description of both mineralogical and geochemical data. Graves Nunataks 95209 and ALHA 81187 exhibit intermediate characteristics and appear to have experienced higher degrees of melting than “undepleted” acapulcoites, with resultant loss of troilite, and perhaps incipient silicate partial melting. The high REE abundances observed in the minerals of these meteorites may have resulted from melting of Ca-phosphates, with subsequent redistribution of the REE among the silicates.

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Introduction: The acapulcoite-lodranite clan of primitive achondrites provides us with a view of ultrametamorphism of chondritic parent bodies. Acapulcoites are highly metamorphosed chondritic materials, in which melting occurred in the Fe,Ni-FeS system, but probably not in the silicate system [1,2]. Lodranites experienced higher temperatures, including partial melting of the silicate system leaving basalt-depleted residues [2,3]. Some intermediate and hybrid members of this clan are also known. Migration of both the metal-sulfide and silicate melts appears to have been complex [2,4]. Study of new members of this clan will yield important information regarding the physics and chemistry of magmatism on asteroidal bodies early in solar system history. Here we present the preliminary results of our study of the new lodranite GRA 95209, and discuss its classification and the origin of the clan.

Petrology: GRA 95209 is a metal-rich stone containing regions of different textures and metal contents [5]. Our thin section contains regions of equigranular, relatively fine-grained (0.2-0.3 mm) silicates similar to acapulcoites, and regions with coarser grain size (0.6-1.0 mm) more similar to lodranites. GRA 95209 is relatively magnesian; average olivine is Fo_{92.6} with a molar Fe/Mn of 14.3. Average low- and high-Ca pyroxene compositions are Wo_{3.3}En_{89.5}Fs_{7.2} and Wo_{43.0}En_{53.5}Fs_{3.5} with molar Fe/Mn of 9.0 and 7.6. Plagioclase is Or_{1.8}Ab_{80.7}An_{17.5} in composition, similar to that in paired lodranites Y-791491, Y-791493 and acapulcoite ALHA81187 [2,3].

Geochemistry: We have performed INAA on splits from two samples of GRA 95209. One has Na/Sc, Sm/Sc, Sm/Yb and Eu/Yb like those of acapulcoites and is distinct from all other lodranites (e.g. Fig. 1). The lithophile element composition of this sample gives no evidence for loss of a silicate partial melt. The Ir/Ni ratio is slightly higher, and Se/Co slightly lower in this sample compared to most acapulcoites, consistent with some loss of a metal-sulfide partial melt. The second split has Na/Sc and Eu/Yb ratios like those of acapulcoites, but low Sm/Sc and Sm/Yb ratios, more like those of lodranites (Fig. 1). Its REE pattern similar to that of lodranite Y-8002 [6]. These characteristics may be consistent with either loss of a low degree silicate partial melt, or slight under-sampling of phosphates. These scenarios remain to be fully evaluated. Siderophile and chalcophile element data for this split are incomplete.

Discussion: The classification of acapulcoites and lodranites is based largely of petrographic criteria [1,3]. However, this clan is heterogeneous in textures, mineral compositions, O-isotopic compositions and bulk lithophile, siderophile and chalcophile element contents. This makes clear-cut classification difficult; EET 84302 is considered a transitional lodranite based on petrography, but is an acapulcoite based on bulk rock composition [2,3]. GRA 95209 is considered a lodranite based on petrography [5], but again, we find that the bulk rock composition is more similar to acapulcoites, and quite distinct from that of lodranites (Fig. 1). The lesson here may be that the acapulcoite-lodranite clan is too heterogeneous to allow simple pigeonholing of its members into distinct groups. We suggest that reevaluation of the classification of rock types in this clan is in order.

GRA 95209 appears to be ultrametamorphosed chondritic material, rather than a partial melt residue in the sense of lodranites. The silicate fraction of GRA 95209 shows no strong evidence for loss of a basaltic melt, in contrast to lodranites. Minor reduction in the Se/Co ratio could indicate some loss of a metal-sulfide melt, but less than we observed for EET 84302. This is curious in view of the petrographic evidence for extreme heterogeneous distribution of metal in GRA 95209 [5].

References: [1] McCoy et al. (1996) *GCA*, 60, 2681. [2] Mittlefehldt et al. (1996) *GCA*, 60, 867. [3] McCoy et al. (1997) *GCA*, 61, 623. [4] McCoy et al. (1997) *GCA*, 61, 639. [5] McCoy and Carlson (1998) *LPS XXIX*, Abstract #1675. [6] Torigoye et al. (1993) *Proc. NIPR Symp. Ant. Met.* 6, 100.

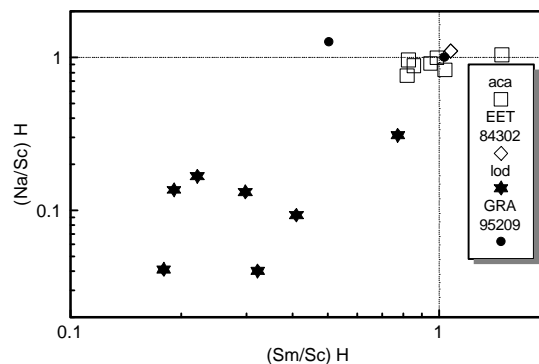


Fig. 1. H chondrite-normalized lithophile element ratios for acapulcoite-lodranite clan meteorites. Data are from this study and numerous literature sources.

ZINC CONTENTS OF UREILITE SILICATES. W. Klöck¹, K. Nakamura¹, M. Maetz², P. Arndt², ¹Institut für Geologische Wissenschaften, Universität Halle, Domstr.5, D-06108 Halle, Germany (kloeck@geologie.uni-halle.de), ²Max-Planck-Institut für Kernphysik, P.O. Box 103980, D-69029 Heidelberg, Germany

Bulk zinc abundances of ureilites are comparable to the zinc contents of CI-chondrites, but the distribution of zinc between different silicate mineral phases is not well known. Generally ureilites consist of euhe-dral olivines and pyroxenes with minor amounts of rare phases like chromite and daubreelite. In addition, they contain some metallic iron, either on grain boundaries between the silicates or as small inclusions predominantly in olivines.

Olivines and pyroxenes of several ureilite meteorite samples were analyzed using the PIXE facility in Heidelberg and the resulting data are compiled in Table 1. Major element compositions of the minerals were obtained by SEM-EDX and iron was used as an internal standard for the PIXE data reduction.

Olivines and pyroxenes of all ureilites, except Goalpara, contain between 100 and 500 ppm Zn. Generally Zn is higher in olivines compared to pyroxenes. In the Goalpara ureilite, however, olivines are much lower in Zn compared to pyroxenes. The levels of Zn in the silicates do in all cases agree with the bulk zinc data, except for Dyalpur, where the reported bulk zinc content is much lower compared to our PIXE data. Our present explanation for this discrepancy is a possible inhomogeneous distribution of Zn in this meteorite.

For comparison, three ordinary chondrite samples were analyzed, and as expected, silicates in these meteorites contain only minor amounts of zinc[1,2]. In ordinary chondrites, chromites were shown to be the host phases of Zn, whereas in the ureilites the silicates contain at least a major fraction of the bulk Zn-content. Chromites in Novo-Urei are very rare and contain on average about 0.8 wt% ZnO. We estimate that at least 90% of the bulk zinc content is contained in the silicates in the case of Novo-Urei. Zn contents of silicates and chromites are consistent with an estimated modal abundance of 20% pyroxenes and 80% olivines for the Goalpara ureilite.

The reason for the low levels of zinc in Goalpara olivines is not yet understood. The low Zn contents of the olivines explains the low bulk zinc content of 84 ppm compared to the bulk zinc content of 266 ppm for Novo-Urei[3]. Kenna, Novo-Urei and Dyalpur are weakly to moderately shocked samples, whereas Goalpara and Dar al Gani 084 experienced higher shock pressures and temperatures, as indicated by petrographic studies [4]. Bulk zinc contents of the more heavily shocked ureilites are lower compared to the

weakly shocked ureilites [3]. Therefore we assume that Zn might have been lost from the olivines by reheating caused by impact processes. Further studies should reveal if abundances of the volatile element zinc in meteoritic silicates can serve as an indicator for shock processes and the related thermal history of meteorites.

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Table 1. Zinc contents of ureilite silicates

	Goalpara		Kenna		Novo-Urei		Dyalpur		Dar al Gani 084	
	Oli	Px	Oli	Px	Oli	Px	Oli	Px	Oli	Px
Zinc (ppm)	10	310	280	210	270	220	540	330	240	90
Bulk zinc (ppm)	84		181		266		271			

IN SITU LASER MICROANALYSIS OF OXYGEN ISOTOPES IN UREILITES. G. J. MacPherson¹, R. D. Ash^{1,2}, and D. Rumble III², ¹Department of Mineral Sciences, MRC-119, National Museum of Natural History, Smithsonian Institution, Washington DC 20560, USA. ²Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Road NW, Washington DC 20015-1305, USA (glenn@glenm.si.edu).

Among the more enigmatic features of ureilites is the observation [1] that their bulk oxygen isotopic compositions as a group define a line of slope ~ 1 on a three-isotope O diagram, and this line is approximately the same as an ^{16}O -poor extension of the Allende CAI mixing line. This is generally taken to mean [1] that the ureilites are not related to each other by igneous processes within a single differentiated parent body, and that their bulk isotopic compositions are inherited from nebular rather than planetary processes, even though many features of these rocks indicate that they formed by igneous processes [e.g., 2,3, etc.]. Clayton and Mayeda [1] noted that members of the Group I (high Fe; [4]) ureilites appear to define 2 subgroups that differ from each other in $\Delta^{17}\text{O}$, and within each of which the oxygen isotopic data falls approximately along a slope- $1/2$ line on a three isotope diagram. More recent work has suggested that the Group I ureilites may consist of as many as four subgroups [5,6]

We analyzed individual mineral grains *in situ* within polished pristine slices of the Group I ureilites Kenna and Novo Urei, using the UV laser probe at the Carnegie Institution [7], and following SEM characterization of the slices. The beam diameter of the laser probe was approximately 400–500 μm . Precision of the data is better than 0.10‰ in $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$. Data for olivine and low-Ca pyroxene in each meteorite are given in Table 1, along with bulk data for the two meteorites from [1]. The Kenna olivine and pyroxene data are within analytical error of each other, although they appear to disperse along a line of slope close to $1/2$. Our mineral data for Kenna bracket the bulk meteorite composition in $\delta^{18}\text{O}$ but are slightly higher in (although within error of) $\delta^{17}\text{O}$ relative to bulk. The Novo Urei olivine and pyroxene points are clearly resolved from one another, with the pyroxene being higher in $\delta^{18}\text{O}$ by $\sim 0.3\text{‰}$ relative to the olivine. As with Kenna, the Novo Urei data define a line of low slope. The enrichment of pyroxene in ^{18}O relative to the olivine in Novo Urei is consistent in sign with igneous partitioning between the two

minerals. Unlike Kenna, our mineral data for Novo Urei do not bracket the bulk meteorite composition in $\delta^{18}\text{O}$ but rather are enriched in that isotope. It is likely that there is a ^{18}O -depleted phase (s) in Novo Urei not represented by our data. The Novo Urei mineral data are also slightly higher in $\delta^{17}\text{O}$ relative to bulk. For both meteorites, we attribute the displacement of our data by $\sim 0.1\text{‰}$ to higher $\delta^{17}\text{O}$ from the respective bulk compositions to systematic analytical differences between the Chicago and Carnegie labs. Weighted least-squares regression of combined mineral data for both meteorites gives a slope of 0.2712 ± 0.4346 , within error of a slope- $1/2$ (mass dependent fractionation) line.

The data thusfar are obviously limited and not conclusive, but are nonetheless entirely consistent with an igneous origin for both ureilites, possibly on the same parent body. This conclusion is consistent with the suggestion of Clayton and Mayeda [1] for these meteorites, but differs from that of [8] based on ion probe analyses of two Antarctic ureilites.

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TABLE 1.

	$\delta^{18}\text{O}$	$\delta^{17}\text{O}$	$\Delta^{17}\text{O}$
Novo Urei pyroxene	7.67	3.06	-0.93
Novo Urei olivine	7.34	2.97	-0.85
Kenna pyroxene	7.59	2.99	-0.96
Kenna olivine a	7.5	2.97	-0.93
Kenna olivine b	7.59	3.04	-0.91
Novo Urei bulk [1]	7.21	2.76	-0.99
Kenna bulk [1]	7.54	2.9	-1.02

OXYGEN ISOTOPE VARIATION IN THE BENCUBBIN METEORITE: AN EXOTIC COMPONENT IN THE MATRIX? I. A. Franchi, A. S. Sexton, and C. T. Pillinger, Planetary Sciences Research Institute, Open University, Milton Keynes MK7 6AA, UK (i.a.franchi@open.ac.uk).

Introduction: Bencubbin remains an enigmatic meteorite, being composed of subequal proportions of metal and silicate clasts together with a few chondritic clasts welded together with a shock melted matrix [1]. The silicate clasts are large broken fragments (up to 1.5 cm) and yet have chondritic textures and composition [2]. Models describing the origin of Bencubbin have problems accounting for many of these unusual features. The O isotopic composition of this meteorite is also somewhat unusual, the main silicate clast showing a similarity to CH and CR chondrites [4] and the chondritic clasts having quite different compositions [3]. This work is aimed at looking at the isotopic variation of the main silicate clasts and their relationship to the, so far neglected, matrix material.

Technique: The samples were broken from a slab of the meteorite with a small stainless steel chisel. The slab (50 × 15 × 5 mm), polished on one side, contained at least three distinct silicate clasts and considerable amounts of matrix material. Four samples each of the clasts and the matrix were obtained, weighing from 1 to 10mg. The samples were analysed using a laser fluorination technique [5].

Results and Discussion: The clast samples display a very narrow range in $\delta^{18}\text{O}$ around +1‰, although one sample does have a $\delta^{18}\text{O}$ value of -1‰ (fig) possibly due to incomplete fluorination of this sample. The $\Delta^{17}\text{O}$ value of the four clast samples is $-2.32 \pm 0.035\text{‰}$. This suggests that the clast samples represent a homogeneous reservoir. This is in contrast to the range of compositions displayed by chondrules from ordinary chondrites (OC) [6], clearly indicating some considerable differences in their formation. Alternatively, such isotopic homogeneity would be characteristic of large scale melting, perhaps associated with an impact origin [2].

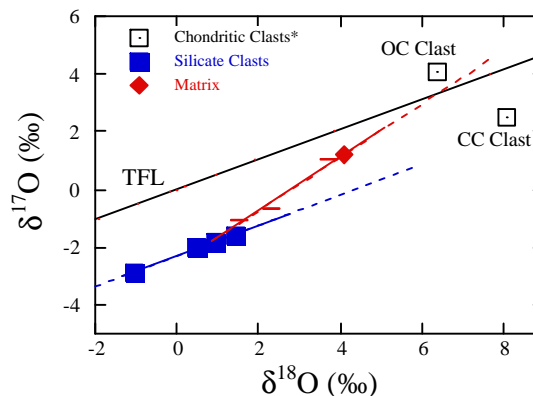
The four matrix samples extended the range of $\delta^{18}\text{O}$ values to over +4‰ and show a much wider range in $\Delta^{17}\text{O}$, with values up to -0.91‰. They appear to define a mixing line, one end member being the silicate clasts (fig). However, two of the matrix samples are strongly influenced by the other end-member component(s).

The two other O reservoirs so far identified in Bencubbin are the ordinary and carbonaceous chondrites [3]. The mixing line does not appear to be with either one of these components (Fig.), although a combination of the two could produce a suitable end

member. However, this would require that approximately 50% of the matrix was this chondritic component. This is unlikely as no such clasts were visible in the slab studied and they are generally very rare in the meteorite.

Chondrules from the CR chondrites have a very similar range of oxygen isotopic compositions to the Bencubbin matrix samples [4]. However there is no other evidence of any distinctive, relict CR chondrule material in Bencubbin.

An alternative mechanism to account for the observed mixing line may be for a small amount of a component with a more extreme O isotopic composition, possibly present in the regolith prior to the shock melting event or perhaps associated with the impact event. This possibility remains speculative but would at least allow the melt to be dominated volumetrically by the silicate clasts. Detailed investigation of compositional variation in the matrix should help constrain these possibilities.



Plot of O isotopic composition of silicate clasts and matrix in Bencubbin. *Data from [3].

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CONSTRAINTS ON THE FORMATION HISTORY OF BRACHINITES FROM RARE EARTH ELEMENT DISTRIBUTIONS. M. Wadhwa¹, J. Zipfel² and A. M. Davis³, ¹Department of Geology, The Field Museum, Roosevelt Rd. at Lake Shore Drive, Chicago, IL 60605, ²Max-Planck-Institut für Chemie, PO 3060, 55020 Mainz, Germany, ³Enrico Fermi Institute and Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637.

Introduction: The brachinite group of primitive achondrites is currently comprised of Brachina, Eagle's Nest, Hughes 026, Reid 013 and ALH84025. There is no consensus on how these igneous-textured, olivine-rich rocks (79–93 vol% olivine) were formed. While some authors favor a residual origin [1,2], others have suggested that the brachinites are cumulates [3–5]. In light of the 4564 Ma Mn-Cr age of Brachina [6], it is important to determine the petrogenesis of these meteorites, since this could place constraints on the earliest igneous processes on asteroids. With the aim of constraining their formation history, we have initiated a trace element study of the brachinites.

Experimental: Bulk chemical data for Hughes 026 and Reid 013, were obtained by INAA in Mainz. Minor and trace element abundances were measured in individual minerals in polished thin sections of Brachina, Hughes 026 and ALH84025 by ion microprobe in Chicago.

Results and Discussion: Hughes 026 has a bulk REE pattern that is LREE-enriched ($\text{La} \sim 2 \times \text{CI}$; $\text{La/Yb} \sim 5$). As has been suggested for Eagle's Nest [7], this LREE-enrichment is most likely the result of terrestrial weathering. In contrast, Reid 013 appears to be LREE-depleted (similar to ALH84025 [3]) and has the lowest REE abundances among the brachinites ($\text{La} \sim 0.06 \times \text{CI}$).

Hughes 026 and Reid 013 have bulk depletions in Na and K (by a factor of ~ 10 relative to CI), indicating depletion in plagioclase similar to that in ALH84025 [3] and Eagle's Nest [7]. We note that among the brachinites, Brachina is exceptional in its near-chondritic lithophile element abundances. Also, Hughes 026 is exceptional in its significant depletion in Ir ($0.02 \times \text{CI}$) and Ni ($0.03 \times \text{CI}$).

In Brachina, ion microprobe analyses show homogeneous distributions of REEs in all minerals. Apatite has an LREE-enriched pattern ($\text{La} \sim 70 \times \text{CI}$; $\text{La/Yb} \sim 4$) with a small negative Eu anomaly ($\text{Eu/Eu}^* \sim 0.75$). Plagioclase is also LREE-enriched ($\text{La} \sim 2.5 \times \text{CI}$; $\text{La/Dy} \sim 8$) and has the characteristic positive Eu anomaly ($\text{Eu/Eu}^* \sim 6$). Augite has an LREE-depleted pattern ($\text{La} \sim 3.5 \times \text{CI}$; $\text{La/Yb} \sim 0.5$) and moderate Eu anomaly ($\text{Eu/Eu}^* \sim 0.5$). Olivine has low REE abundances, but its REE pattern is V-shaped, which we interpret as resulting from terrestrial weathering.

In Hughes 026, we analyzed apatite, augite and olivine; no plagioclase was found. As in Brachina, apatite has an LREE-enriched pattern, but REE abundances are lower than in Brachina ($\text{La} \sim 13\text{--}42 \times \text{CI}$). One of the augite grains analyzed has an LREE-depleted pattern ($\text{La} \sim 0.4 \times \text{CI}$; $\text{La/Yb} \sim 0.1$), but another has a V-shaped REE pattern, most likely from terrestrial weathering. Olivine may be unaffected by such weathering, as it has an LREE-depleted pattern ($\text{La} \sim 0.02 \times \text{CI}$; $\text{La/Yb} \sim 0.04$).

In ALH84025, we analyzed augite and olivine. We also measured a small ($\sim 15 \mu\text{m}$) whitlockite grain, the only Ca phosphate we could locate; no plagioclase was found. Augite is LREE-depleted ($\text{La} \sim 0.3 \times \text{CI}$; $\text{La/Yb} \sim 0.07$), while the olivine has very low REE abundances ($\text{La} < 0.01 \times \text{CI}$) and a steep LREE-depleted pattern ($\text{La/Yb} < 0.02$). Therefore, the LREE depletion in the ALH84025 bulk rock [3] is because augite and olivine are the main carriers of REEs (whitlockite does not contribute significantly owing to its small abundance and low REE concentrations). We did not find any carrier for the positive Eu anomaly noted by [3] in the ALH84025 bulk rock.

Of the three brachinites in which REE microdistributions were measured, ALH84025 appears to be least affected by weathering, while Hughes 026 is most weathered (supported by LREE-enrichment in its bulk rock REE pattern). Brachina may have been mildly weathered, so that only olivine was affected. REE microdistributions in Brachina and ALH84025 are consistent with extensive reequilibration and homogenization. If these rocks are cumulates, the signature of fractional crystallization was not preserved in the REE distributions in augite. Further analyses of the most differentiated (and possibly least weathered) samples, ALH84025 and Reid 013, will be required to better evaluate whether or not these samples may be of cumulate or residual origin.

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BRACHINITES: RESIDUES FROM LOW DEGREES OF MELTING OF A HETEROGENEOUS PARENT BODY. C. A. Goodrich, Max-Planck-Institut für Chemie, P.O. 3060, 55020 Mainz, Germany (goodrich@mpch-mainz.mpg.de).

Introduction: Brachinites are a small group of primitive achondrites (Brachina, ALH 84025, Eagle's Nest, Hughes 026, and Reid 013/Nova 003) distinguished by common mineralogy (olivine + augite \pm plagioclase \pm orthopyroxene) and relatively Fe-rich olivine (Fo ~65–68). Brachina is a fine-grained (0.1–0.3 mm) equigranular assemblage of 5–9% augite, 10–11% plagioclase, and a trace of orthopyroxene [1,2], and has a nearly flat REE pattern at $\sim 2 \times \text{CI}$ [3]. It was interpreted by [2] to be an almost primitive meteorite that experienced only a small amount of melting. In contrast, ALH 84025 is coarser-grained (up to 2.7 mm) with prismatic olivine shapes, and contains only olivine + 4.2–15% augite [3]. It has a LREE-depleted pattern with La $\sim 0.28 \times \text{CI}$ and Lu $\sim 0.65 \times \text{CI}$ [3]. Eagle's Nest is similarly coarse-grained, and contains only olivine + $\sim 7\%$ augite [4]. Warren and Kallemeyn [3] suggested that both ALH 84025 and Brachina are cumulates.

Wadhwa et al. [5] studied the ^{53}Mn - ^{53}Cr system of Brachina and found that ^{53}Mn ($t_{1/2} = 3.7$ Ma) was alive at the time of the last Cr isotopic equilibration in this meteorite. Relative to the angrite LEW 86010, they obtained an age of 4563.7 ± 0.9 Ma, ~ 2 Ma younger than CAIs [6]. This extremely old age seems easy to reconcile with the interpretation that Brachina is a residue of a very small amount of melting. However, if brachinites are cumulates, a more extensive igneous history would be required, and this age would be much more remarkable.

Here I present results of equilibrium partial melting calculations designed to determine whether brachinites can be modeled as simple residues of low degrees of melting of chondritic material. I focus initially on Brachina, ALH 84025 and Eagle's Nest.

Method: Calculations were performed using MAGPOX [7] at 10 b pressure. I assumed that FeO content was a free parameter and could be adjusted to produce the desired mg for residual olivine. This assumption is justified under the hypothesis that both the total Fe and oxidized Fe contents of the precursor materials of all primitive achondrites were determined by nebular processes [8].

Results: A Brachina-like residue can be produced by 1–2% melting of material having Ca/Al = CI, Si/Mg at the high end of the CC range, and alkali contents at the high end of the CC range (necessary to ensure that the low-Ca pyroxene is orthopyroxene rather than pigeonite), if Ca/Mg and Al/Mg are ele-

vated to $\sim 1.7 \times \text{CI}$. Such material could be produced by addition of $\sim 1.5\%$ of 1500°K high-temperature condensate (HTC [9]) to an average CC composition.

This material could not, however, also yield ALH 84025- and Eagle's Nest-like residues (olivine + 7–9% augite, assuming a mean for ALH 84025). Starting materials with superchondritic Ca/Al are required to produce such residues. For example, an average CC composition with high alkali contents and Ca/Al increased to $\sim 1.5 \times \text{CI}$ (which can be achieved by subtraction of $\sim 0.7\%$ corundum) could produce an olivine-augite residue with $\sim 8\%$ augite at 9–11% melting (which is consistent with the Lu depletion in ALH 84025 assuming that original REE abundances were $\sim 2 \times \text{CI}$).

Discussion: These calculations suggest that Brachina, ALH 84025 and Eagle's Nest could have originated as residues of low degrees of melting (1–10%) of materials which showed small deviations (in Si/Mg, Ca/Al and Ca/Mg) from the range of known CC compositions. These deviations can be attributed to nebular fractionation processes such as excess accretion of $\sim 1.5\%$ HTC and incomplete accretion of $\sim 0.7\%$ corundum. These degrees of fractionation do not seem implausible, particularly in light of the much larger nebular fractionations postulated for precursor materials of angrites [10] and ureilites [11]. Thus, it is not necessary to invoke extensive igneous events such as large-scale melting and fractional crystallization in the ~ 2 Ma [5] between formation of CAIs and formation of Brachina.

Furthermore, these calculations indicate that if Brachina, ALH 84025 and Eagle's Nest are derived from a single parent body, then that body was heterogeneous in major element composition to a greater degree than chondrites, and was not homogenized by melting.

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RARE-EARTH-ELEMENT ABUNDANCE OF PYROXENE AND PLAGIOCLASE IN A PRISTINE EUCRITIC BASALT, YAMATO 75011,84. T. Arai¹, H. Takeda², J. J. Papike³, C. K. Shearer³, and M. Miyamoto¹, ¹Mineralogical Institute, Graduate School of Science, University of Tokyo, Hongo, Tokyo 113-0033, Japan, ²Research Institute, Chiba Institute of Technology, Tsudanuma, Narashino, Chiba 275-0016, Japan, ³Institute of Meteoritics, Department of Earth and Planetary Science, University of New Mexico, Albuquerque NM 87131-1126, USA.

Introduction: Eucrite basalts are products of the earliest planetary volcanism in the solar system. However, they generally suffered from brecciation and metamorphism on the parent body [e.g., 1] and thus their mineral chemistries and crystallization ages tend to be reset [e.g., 1,2]. Yamato (Y) 75011,84 is a basaltic clast in a polymict breccia and rarely preserves its primary texture, mineral composition, and crystallization age [3]. We analyzed REE abundance of pyroxene and plagioclase by ion microprobe and ensured its pristinity by comparing the REE abundance of the bulk clast with that of the parent magma calculated from the mineral compositions.

We investigated Y 75011,84 eucrite basalt from NIPR by chemical map analysis and analyzed REE of the spots of the earliest crystallization by the Cameca IMS 4f instrument operated by the University of New Mexico/Sandia National Laboratories Ion Microprobe Facilities.

Results and Discussion: Average REE abundance of pyroxenes and plagioclases is compared with bulk-clast REE abundance in Fig.1. All pyroxene cores from four zoned pyroxenes show almost identical abundances for HREE, although the LREE are scattered due to their extremely low concentration. Although analyses of Eu for all cores fall below detection limit, all have negative Eu anomaly. Two plagioclase grains were analyzed and their REE abundances are similar to each other, except Er and Yb. Pun and Papike [4] analyzed pyroxene cores from probably a similar clast (Y 75011,96) as Y 75011,84. However, REE abundances of

their cores are ~2–4 higher than that of our cores. This suggests that pyroxene cores in Y 75011,84 could be more primitive and more likely preserve compositions of a primary magma.

REE abundance of a parent magma was calculated from average REE abundances of pyroxenes and plagioclases, using partition coefficient *D* of McKay et al. [5] and Phinney and Morrison [6] respectively. Both calculated parent melts have REE abundance of ~20–30 CI chondrite and a fairly flat pattern, which well matches the bulk-clast REE abundance by Palme and Ikeda (1994, personal communication). This strongly supports a fact that cores of pyroxene and plagioclase in Y 75011,84 clast record the REE compositions of the parent magma.

The REE abundance of the parent magma for Y 75011,84 eucrite basalt is higher than those for REE-enriched ordinary eucrites, such as Nuevo Laredo and Stannern [7]. The flat REE pattern despite the highly enriched REE abundance, can be explained by the co-crystallization of pyroxene and plagioclase from the melt, in which REE abundance of the two minerals have complimentary trends.

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Fe-Ni METAL BEARING UNIQUE EUCRITE EET92023: ITS PETROGRAPHY, SIDERO-PHILE CONCENTRATIONS AND PETROGENEIS. K. Kaneda¹ and P. H. Warren², ¹Mineralogical Institute, Graduate School of Science, University of Tokyo, 113-0033, Japan, ²Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA.

EET92023 is a cumulate eucrite that superficially resembles Moore County. Mittlefehldt et al. [1] used INAA to determine that it has extraordinarily high siderophile concentrations, and tentatively suggested that it might be a clast from a mesosiderite. We have studied its texture and mineralogy, and used INAA and RNAA to determine a larger suite of siderophile elements.

The mode is 59.1% pyroxene, 38.9% plagioclase, 0.8% troilite, 0.5% Fe-Ni metal, 0.5% silica, plus minor phosphate, chromite and ilmenite. Metal grains, up to ~300 μm in diameter, are consistently anhedral and equigranular, unlike the metals of mesosiderites, which are chaotically xenomorphic. Fe-Ni metals are mainly divided into two phases, low Ni phase (kamacite) and high Ni phase (taenite), as in ordinary chondrites and iron meteorites. Taenite grains show strong chemical zoning. From core to rim, Ni contents increase from ~39 to ~54 wt%, often with a compositional discontinuity near grain edges. This discontinuity might be related to a change of texture, from cloudy interior to outer taenite rim (OTR) [2]. High Ni contents (> about 48 wt%) of the rims and the possible presence of OTR suggest they may be tetrataenite.

Because the boundary between kamacite and taenite is sharp and linear, a planar diffusion model was applied to the Ni zoning profile in taenite to estimate the approximate cooling rate of Fe-Ni metal. Calcium-phosphates (apatite and whitlockite) are scattered in this thin section, so the modeling included the effect of P on diffusion coefficients [3]. The phase diagram adopted in this work [4] was determined by investigation of metal phases in meteorites. Calculated cooling rate of Fe-Ni metal in EET92023 is ~4°C/My from ~700°C to ~300°C.

Although the profiles of Fe-Ni metal indicate very slow cooling, by eucrite standards, other textures observed in EET92023 suggest that cooling was fast, by cumulate eucrite standards. Augite exsolution lamellae in pyroxenes are fairly thin (generally <0.5 μm , spaced several micrometers apart). Pyroxenes are commonly zoned. Small pyroxenes (<~300 μm in diameter) have constant mg [$\text{Mg}/(\text{Mg} + \text{Fe})$] at ~0.51, but in larger pyroxenes mg decreases from core (0.58) to rim (0.51). Larger grains also show Ca zonation, with augite exsolution lamellae increasing in

thickness toward the rim. Some rims even give way to discrete augite and low-Ca pyroxene dominated regions (50–100 μm across), possibly produced as primary-igneous (not exsolved) augite + low-Ca pyroxene. Plagioclases are typically rectangular with rounded edges, and retain traces of euhedral Ca-rich (~An95) cores. Relatively Na rich rims (An80–68) partly cover euhedral ~ subhedral plagioclases.

Our analyses of two powder samples from a 600-mg chip confirm a strong bulk-compositional similarity to Moore County, except for siderophile elements. The siderophile contrast is even more dramatic than suggested by [1], who reported results in terms of EET92023/MC ratios, e.g., Ir = 100 \times . Our results (averaged, in $\mu\text{g/g}$) for Ni, Ge, Re, Os, Ir and Au are 1230, 1.41, 0.0053, 0.046, 0.050 and 0.015. Expressed as an EET92023/MC ratios, the Os result is 15000 \times . These data hint at possible kinship with mesosiderites, because CI-normalized Re/Ir (1.33 \times) and Ge/Ir (0.40 \times) resemble, in dampened form, similar fractionations in mesosiderites.

This eucrite should not be classified as a normal cumulate eucrite, because well-preserved zoning trends and weakly developed pyroxene exsolution structures indicate comparatively rapid near-solidus cooling, while the high FeNi-metal and siderophile abundances suggest origin from an impact melt. The slower cooling from ~700°C to ~300°C inferred from taenite zoning suggests that the rock was relocated to a slower-cooling environment while still at roughly 700°C. This transition might have been caused by burial under impact ejecta, or possibly, if the mesosiderite clast model is correct, by involvement in a general reheating of mesosideritic materials at ≥ 4.47 Ga, or localized reheating at 4.5–3.9 Ga [5]. However, the FeNi-metal and siderophile enrichments and fractionated Ge/Ir and Re/Ir ratios (i.e., the only evidence for possible mesosiderite kinship) must date from the initial igneous crystallization of EET92023.

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HOWARDITE-EUCRITE-DIOGENITE MAGMA OCEAN PETROGENESIS: EQUILIBRIUM OR FRACTIONAL CRYSTALLIZATION? P. H. Warren, Institute of Geophysics and Planetary Physics, University of California–Los Angeles, Los Angeles CA 90095-1567, USA (pwarren@ucla.edu).

Righter and Drake [1] recently adduced evidence from siderophile element partitioning supporting the hypothesis that core formation on the HED parent asteroid occurred at very high temperature, implying (or confirming) the existence of a primordial magma ocean. These same authors also proposed [2] that crystallization of the HED magma ocean (MO) was an equilibrium process for all but the final 20% of the solidification. The model assumes that at 80% solidification “convective lockup” finally caused crystal settling. The MO then adjusted itself into a layer of solid diogenite and residual melt, which soon solidified into the eucritic crust. The equilibrium premise of this model seems implausible. Actually, although Righter and Drake label and model their scenario as equilibrium, their discussion invokes “initial” formation of a small volume of dunite below the diogenites, in a deviation from true equilibrium solidification.

The physical arguments cited for equilibrium crystallization are oversimplified. Turbulent convective flow is supposed to keep all crystals suspended in the melt up to 80% MO crystallization. Convective vigor is modeled based on a form of the Rayleigh equation with $Ra \propto D^5$, but this form applies only to systems with major active heat sources. The MO may have melted via internal heating, but during its crystallization the primordial heat source (^{26}Al ?) might easily have become negligible. The more general form of the Rayleigh equation has $Ra \propto D^3$ — a whopping difference. The model ignores the potential for large suspended crystal fractions to create regional compositional (clustered crystals vs. melt) buoyancy forces that, given realistic assumptions about convection complexity (layering, unsteadiness of flow), can easily overwhelm the thermal convective force, even at crystal fraction of <0.03 [3].

One of the most fundamental, basic, defining characteristics of diogenites is their tendency to be almost monomineralic orthopyroxenite. Conveniently, Bowman et al. [4] have just published modes for 20 diogenites (I regard several presumptive pairs as single meteorites). The average mode is $94 \pm 9\%$ pyroxene, $2.5 \pm 8\%$ olivine and $1.3 \pm 4\%$ silica. Excluding two oddballs rich in either olivine or silica, the means are $94.8 \pm 3.7\%$ pyroxene, $0.8 \pm 1.3\%$ olivine and $0.4 \pm 0.3\%$ silica. Literature modes for numerous additional diogenites are uniformly close to this average. It seems

clear that the overall olivine/pyroxene volume ratio for diogenites is <0.3 and vastly less than 1.

Equilibrium crystallization requires that all crystals remain in constant close proximity to the residual melt. This may in principle be achieved by convective stirring, but it implies that the crystal proportions are uniform throughout the system; the olivine/pyroxene ratio is as high at the top of the MO as at the bottom. The olivine/pyroxene ratio at 80% solidification (o/p_{80}) will depend on the initial MO composition (i.e., essentially the bulk-silicate composition of the asteroid). For the bulk composition assumed, o/p_{80} is 1.19 (by mass; from Fig. 6 of [2]), i.e., grossly inconsistent with the olivine/pyroxene ratio of diogenites. Alternative initial compositions could in principle yield an $o/p_{80} \ll 1$, but the only primitive materials with much lower olivine/pyroxene than the composition modeled are enstatite chondrites, which are far too low in FeO/MgO to be related to eucrites. In general, primitive materials have uniform MgO/SiO₂. A type with low enough olivine/pyroxene and yet high enough FeO/MgO to satisfy the demands of the equilibrium MO model probably does not exist.

A key advantage claimed for the equilibrium MO model over fractional crystallization models [e.g., 5, 6, 7], is that fractional crystallization tends to predict implausibly high FeO in the late-stage melts that both models stipulate played a key role in genesis of the eucrites. The main problem with this argument is that the MO was almost certainly not a simple closed system. Primitive, high MgO/FeO material was probably accreting into it from space, and it may well have been periodically replenished with primitive melt from a deep layer of the asteroid that avoided total involvement in the initial MO. But this notion of open-system behavior of the HED asteroid’s MO is not new [8].

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